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The design and marketing of a new fail-safe device for gas appliances.

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THE DESIGN AND MARKETING OF A NEW FAIL-SAFE DEVICE FOR GAS APPLIANCES

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ABSTRACT

The mercury flame failure device (F.F.D.) has now been in existence for approximately 30 years and in the United States, Canada and Britain there is now estimated to be a field population of 42,000,000 of these controls, with a current production rate of 2,350,000 units per year. Recently several problems have been identified which threaten the future of the mercury F.F.D., notably the toxicity of the mercury fill, and the relatively short life of the devices under some operating conditions.

This work examines the background to the mercury F.F.D. and the problems associated with it. A new type of F.F.D. was developed, for which patents have been applied. This device was filled with an inert gas, and was found to have all of the advantages of the mercury F.F.D., without the problems associated with the mercury. Prototypes were constructed which had sufficient performance and reliability to substitute for the mercury F.F.D..

Computer programs were developed to enable performance predictions to be made for gas filled devices and design data is given to enable the optimum design parameters to be selected for a particular application. The reliability problems associated with the new device were investigated and suggestions are made to enable maximum reliability to be achieved.

Finally the marketing of the new F.F.D. was studied. The existing market for the mercury F.F.D. was examined and the chances of the new F.F.D. succeeding in this market were considered. It was found that, given competant development, production and enthusiastic marketing, there were no reasons why the new F.F.D. should not succeed in the market place.

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CHAPTER 1

GENERAL HISTORY OF FLAME FAILURE DEVICES

1.1 Industrial Gas Appliances

The development of flame failure devices (F.F.D.'s) was pioneered in industrial gas appliances during the 1930's when the increasing use of thermostatic and other forms of automatic control on boilers and furnaces had resulted in increased chance of flame failure. Moore (1) lists several reasons for this, notably the rapid opening and closing of control valves causing pressure fluctuations in the gas supply, the effects of draughts on throttled back main burner flames, or pilot flames, the blockage of pilots by soot, dirt or corrosion, and finally the "uncouth" human element. The very fact that this new generation of appliances were automatic meant that they would be expected to function for long periods without manual supervision, so large volumes of gas could escape into the atmosphere before detection if a flame were to extinguish. This would result in an explosion hazard, and in the days of town gas a carbon monoxide poisoning hazard.

Consequently a flame failure detection system became a desirable part of a gas appliance control system, and with the cost of industrial appliances being quite high, the extra amount spent on flame failure detection could be easily justified. Thus before the last war many industrial gas installations were fitted with simple mechanical, electrical or electronic devices, many of which were imported from the U.S.A. (2). After 1945 a variety of British made F.F.D.'s began to appear on the market. Honeywell-Brown introduced a flame conductivity system in 1946, and were followed by Radiovisor Patent Ltd who produced a photoelectric detector, but both of these systems used vacuum tube electronics which made them expensive and unreliable. Several companies experimented with cheaper devices based on the bimetallic principle (see section 2.2.), and in 1948 Perl Controls (3) introduced a British version of the thermoelectric F.F.D. (see section 2.3) previously imported from the U.S.A. Since then the thermoelectric device has found widespread application in domestic and industrial appliances due to its cheapness and reasonable reliability.

More recently the advent of cheap solid state electronic components has made relatively low cost electronic F.F.D.'s available, which because of their high speed of operation are now widely used in industry. Table 1 lists a range of flame sensing methods which could be used in an electronic F.F.D. system.

In 1950 the Industrial Gas Development Committee published a report (4) in which were laid down "indispensable characteristics" and "desirable features" for F.F.D.'s as follows:-

(i) Indispensable Characteristics.
Every flame failure device must:-

(a) Entirely prevent gas from being supplied to the main burner until the pilot flame is established.

(b) If fitted correctly be free from an inherent weakness in design which will give rise to failure to danger.

(c) After flame failure, completely stop all gas flow to the appliance, and require manual resetting.

(d) Be actuated only by a properly established pilot flame sited to ignite the main burner without failure or delay.

(e) Where it incorporates a gas - carrying component, have an approved capacity within a permitted pressure loss.

(ii) Desirable Characteristics.
Every flame failure device should:-

(a) Be mechanically satisfactory and readily maintained.
(b) As far as practicable be protected against adjustment by unauthorised persons.
(c) Tolerate reasonable fluctuation in gas pressure, and combustion characteristics.
(d) Be reasonably unaffected by foreign matter.
(e) Tolerate reasonable variations in ambient temperature and air speed.
(f) Tolerate reasonable vibration and mechanical shock.
(g) Cut out when the pilot becomes too short or weak to ignite the gas at the main burner.

These guidelines formed the basis for future development of both F.F.D.'s themselves, and the regulations governing them.

1.2 Domestic Appliances

Generally speaking domestic appliances began to be fitted with F.F.D.'s at a later date than appliances in the less cost conscious industrial market. Here again it was the increasing use of automatic controls that had made this step necessary.

The first gas cookers (circa 1850) were very simple with only a gas tap to control oven temperature, but at the turn of the century the gas thermostat was developed in the U.S.A. This enabled the oven to operate automatically, as the thermostat controlled the temperature by modulating the main burner flame height. However when the flame was reduced by the thermostat there was an increased probability of flame failure, a dangerous situation which was at first circumvented by having a high "by-pass" setting on the thermostat, so that the flame was always sufficiently large to resist extinction. Unfortunately, "safe" by-pass rates meant that low oven temperatures were difficult to control, and thus some cooking operations were made difficult or impossible.

During the 1940's flame failure devices became available on gas ranges made in the U.S.A. (5). At first these were simple bimetallic devices, followed later by thermoelectric devices, but neither of these systems were ideal for cookers and proved to be troublesome. In 1958 the Robertshaw Fulton Company in the U.S.A. developed the mercury F.F.D. (see section 2.4) which for many years has proved to be the best solution to the flame supervision problem in gas cookers. This system proved to be more reliable than the others, and it enabled cooker control systems to be produced which could regulate oven temperatures down as low as 60^{o}C.

Mercury F.F.D.'s became available from British manufacturers from 1965, and initially were only used in the control systems on more expensive cookers in which safety was a sales feature. From January 1 1972, British Gas document WH/71/24 (6) made a F.F.D. a compulsory fitment on a gas oven, if it were to obtain Gas Council approval. Most manufacturers adopted the mercury F.F.D., but some (Parkinson Cowan, Flavel and Main) used thermoelectric F.F.D.'s in at least some of their production. The use of thermoelectric F.F.D.'s on ovens has been made more difficult since August 1976, when standing pilots on gas cookers were banned by British Gas as a fuel saving measure. This meant that thermoelectric F.F.D.'s had to be manually reset (see section 2.3) at the start of each cooking cycle, and the inconvenience of this to the consumer has prompted some manufacturers to change from thermoelectric F.F.D.'s to mercury F.F.D.'s.

At the time of nationalization of the gas industry, (May 1 1949) gas had penetrated 11 million homes in Britain, almost entirely due to gas cookers and water heaters (7). Since then there has been a dramatic increase in the variety of gas appliances used in the British home. Gas heating has been responsible for much of this. Central heating boilers and air heaters are now found in many homes, and these must be fitted with a F.F.D., most of which are the thermoelectric type, although some have been fitted with bimetallic F.F.D.'s. Radiant gas fires are not at present fitted with F.F.D.'s as they are manually controlled, but automatic wall mounted balanced flue convector heaters are fitted with F.F.D.'s, generally of the thermoelectric type.

Water heaters are still widely used in the U.K. These can be of the multipoint type, single point type (geysers) or the storage type. In this field the bimetallic strip F.F.D. has been the most commonly used type, although more recently thermoelectric devices have become popular.

Other appliances include refrigerators, not fitted with F.F.D.s (except those using L.P.G.) due to their low gas consumption, drying cabinets, which have been fitted with all types of F.F.D., and greenhouse heaters which have used mercury and thermoelectric F.F.D.s.

CHAPTER 2

SURVEY OF KNOWN METHODS OF FLAME DETECTION

2.1 Flame Detection Methods

Methods which need an electricity supply to operate them are listed in table 1. They all need a solenoid valve to control the gas flow, and most (except the mercury switch, thermocouple switch, symmetrical diode ultra violet detectors and the salt cell) require an amplifier to give enough power to control the solenoid valve. Although some of these methods have many attractions, their expence has limited them to industrial gas appliances.

Table 2 reviews known methods of flame detection which produce mechanical movement. The porous plug and Curie Temperature devices have only been produced experimentally at the American Gas Association Laboratories by Zielinski (8) and have many problems associated with them. The mercury, thermoelectric and bimetallic devices have all seen extensive use, and their advantages and disadvantages are well known. Their main advantages are that they are cheap to make, reasonably reliable, and are totally self contained, not needing any external power supply. These features have ensured that most domestic appliance F.F.D systems are of one of these types. They are examined in detail in the following sections.

2.2 The bimetallic and unimetallic F.F.D.

In its most basic form this consists of a bimetallic strip which when heated by a pilot flame, bends, and opens a gas valve via some form of mechanical linkage. If the flame should fail the bimetallic strip cools and gradually shuts the valve.

Unfortunately there are a number of serious problems with bimetallic devices. Prolonged use can cause the bimetallic element to warp (1) and hold the gas valve permanently open, and because the actuating mechanism is exposed it is easily tampered with.

An important problem from the appliance manufacturers point of view is that because of the mechanical linkage between the flame sensor and the gas valve, the F.F.D. has to be specially engineered for each application (or vice versa). Both the mercury and thermoelectric devices have a flexible connection between the flame sensor and the valve, which means that a standard device can be sold, which can then be bent to fit all burner configurations.

Many attempts have been made to improve this basic system. One idea was to use a rod surrounded by a tube of different material. The rod and tube which are fixed together at one end expand differentially when heated, and the difference in movement between rod and tube can be used to operate a valve. This system is more rugged that the bimetallic strip version, and is tamper proof. However the movements so far obtainable over a normal operating temperature range are minute unless a very long length is heated, so in general this device can only be used to control a low gas flow. Hence this type of F.F.D. has to be used in conjunction with a gas relay valve. This system was the basis of the Potterton rod type cut out device (1).

Bimetallic discs have been used in some systems such as that produced by De La Rue Gas Developments just after the war (1). Here a pilot flame played on a bimetallic disc and the movement of the disc centre operated a small valve via a system of levers. Again this valve could only control a low gas flow, and a gas relay had to be used in combination with it.

Unimetallic systems have also been developed (2, 9) in which the heat from a pilot causes differential longitudinal expansion between the two sides of a tubular metallic element. This causes a small curvature of the tube which is used to operate a valve. These devices have not been used to any great extent, again due to the need for a gas relay to control a reasonable gas flow.

2.3 The Thermoelectric F.F.D.

This has now become the most popular type of F.F.D. due to its simplicity, ease of manufacture, relatively good reliability and high flow capacity. Figure 1 shows a drawing of a typical device. The thermocouple itself consists of a stainless steel sheath with a constantan wire inserted down its centre, the two being welded together at one end to produce the hot junction. At its other end the stainless steel sheath is brazed to a copper tube, and the inner constantan wire welded to a copper wire, which runs up the centre of the tube. The copper wire and tube are separated by glass fibre insulation, and thus form a low resistance coaxial conductor which can be readily bent without causing a short circuit.

A typical thermocouple produces a minimum open circuit E.M.F. of 25 m.V. at a hot junction temperature of 600^{o}C (12). This voltage although small, is enough to power a small electromagnet providing the circuit resistances are kept low, and this effect is used to operate a F.F.D. Figure 1 shows a common type of valve assembly, in which both the main burner and the pilot are protected by the F.F.D. The thermocouple normally has a resistance between 10mΩ and 25mΩ (12) and the electromagnet resistance is typically 16mΩ , giving a total circuit resistance of approximately 40mΩ . Therefore when the hot junction is heated by a pilot flame, a current in the order of 600 mA will flow, which enables the coil to hold a gas valve open against a spring. If the supervision burner should extinguish, the thermocouple will cool, and the circuit current will gradually fall to below the holding current (~100 mA), when the spring will shut the valve. The thermocouple cannot supply sufficient energy to open the valve automatically, so the valve has to be held open manually by means of the reset button (fig. 1) until the thermocouple produces sufficient current for the magnet to hold the valve open. This F.F.D. has a great advantage over the bimetallic device in that the connection between the flame sensor and valve is flexible, allowing a standard device to be marketed, which can be bent to fit most burner configurations. In some instances the device is modified so that the electromagnet operates a switch, enabling the device to be used in electric boiler control systems, however this device still needs to be manually reset.

The main drawback to the thermoelectric F.F.D. is the need to manually reset the device on start-up. In appliances where standing pilots are permitted (e.g. boilers) this is not too great a problem as the pilot only needs to be relit very occasionally, but in gas cookers where standing pilots are not permitted this is a major disadvantage. Reliability has also been a problem when sensing standing pilots, as the long periods at high temperature result in atmospheric oxygen diffusing through to the hot junction causing it to oxidise. This causes the thermocouple resistance to rise, resulting eventually in complete failure of the device.

Thermoelectric F.F.D.'s are now the subject of a British standard (13), as well as a draft European standard (14).

2.4 The Mercury F.F.D.

The search for a better means of flame detection led to the development of mercury vapour F.F.D.'s in the U.S.A. during the 1940's. The patent for the first practical mercury device was applied for in 1947 by C.A. Cobb of the Missouri Automatic Control Corporation (now White Rodgers) (15). A drawing of this device is shown in fig. 3. It consisted of a phial filled with mercury connected via a capillary tube to a chamber, one wall of which was a flexible metal diaphragm. When the phial was heated by a pilot flame the mercury within it boiled and the resulting pressure forced mercury along the capillary into the chamber. This caused the flexible diaphragm to deflect, and operate a switch. When the flame was removed the phial cooled, and the mercury vapour condensed causing the internal pressure to drop thereby allowing the diaphragm to return to its rest position and open the switch contacts. Although Cobb (15) suggested that any liquid might be used he noted, "Experiments indicate mercury to be the preferred liquid, because it is stable at high temperatures, it is heavy and gravitates well to the opening in the lower end of the bulb chamber, and because its boiling point is high enough so that heavy loading of the spring is not required to maintain the operating temperature of the device safely above temperatures which may occur ambient to a burner in a furnace".

The volume of the phial and the capacitance of the diaphragm (the volume increase per unit pressure increase:- $\frac{\Delta V}{\Delta P}$) were fixed so that at its operating temperature the phial contained only mercury vapour. This limited the maximum deflection of the diaphragm, as once the phial was emptied of mercury, heating to higher temperatures would only result in small pressure increases as expansion of the mercury vapour obeys the gas laws. Thus the phial volume controlled the maximum diaphragm deflection, and the device would not be damaged by overheating the phial. Cobb also stated that by restricting the liquid - vapour interface to the capillary, the pressure surges caused by explosive boiling would be minimised.

This device seemed an ideal answer to the flame monitoring problem. Unlike the thermoelectric device it needed no manual resetting, as it was activated merely by the application or removal of heat from the flame sensing phial. Unlike the bimetallic device there were no exposed working parts which could be tampered with, and the moving parts were well removed from the source of heat so were less likely to become jammed due to oxidation. Another important point was that like the thermoelectric device there was a flexible connection between the sensor and valve part of the device, meaning that the device would not have to be engineered as part of the burner as with bimetallic devices. This mercury device was extensively fitted to boilers and clothes driers in the U.S.A., and is still manufactured albeit with small modifications by the White Rodgers Company.

The Cobb device had one drawback, it was a "flame switch", so to control a gas burner it needed an electricity supply, and a solenoid valve. During the 1950's further work was directed towards producing a mercury device which directly operated a valve rather than a switch. The Robertshaw Controls Company of the U.S.A. developed a solution, and a patent was applied for it by V. Weber in September 1958 (16). A drawing of this device is shown in Fig. 4. In Weber's device the phial and capillary were made from a wide bore tube closed at one end, with a shorter filler wire inserted from the other end. The chamber - diaphragm arrangement of the Cobb device was substituted by a capsule consisting of two flexible diaphragms welded together. This enabled the maximum safe deflection available from a given diaphragm diameter to be approximately doubled. As before, mercury in the phial boiled when placed in a flame and the pressure increase caused the capsule to deflect. As the capsule deflection was not sufficient to give an adequate valve lift by itself, the movement was magnified by a double lever system which operated the valve.

Weber's device was ideal for gas oven control systems, as it operated entirely from flame energy, was potentially very reliable, and had a flexible connection between sensor and valve allowing one F.F.D. design to be used in a variety of burner configurations. As a consequence of these advantages, this type of F.F.D. has become the most common to be fitted to cookers in the U.S.A., Canada and Britain. Since the Weber patent (16) was applied for, further U.S.A. patents were granted (refs. 17 - 23), showing various ways in which mercury F.F.D.'s could be combined with burner control systems.

The Weber type of mercury F.F.D. was expensive to produce due to its complexity, and the need for accurate construction. Since the 1950's advances in the materials and methods of production of flexible capsules have enabled the maximum defections available to be increased from approximately 0.4 mm to 0.9 mm. This has made possible simpler direct acting devices which are cheaper to produce. Figs. 5 and 6 show such a device, made in the U.K. by Harper Wyman Ltd.

CHAPTER 3

PRESENT DAY USE OF MERCURY F.F.D.'S

3.1 Limitations of Mercury F.F.D.'s

The wider use of mercury F.F.D.'s in gas appliances other than cookers has been limited by the poor performance of these devices in the following three areas:-

3.1.1 Limited Flow Capacity

The maximum flow capacity of a typical mercury F.F.D. is in the region of 1 cu. metre per hour at a pressure drop of 0.75 mb. This has prevented such devices being extensively used in industry, where appliances generally require much higher gas flows. For this same reason the device has not been used in domestic central heating installations, which typically use gas at the rate of 1 to 3 cu. metres per hour, and in instant water heaters which have similar consumptions. Thus these large domestic markets have been taken over by thermoelectric and bimetallic devices which can handle larger gas flows.

3.1.2 Slow Response

A typical mercury F.F.D. takes approximately 30 to 60 seconds to respond to the application or removal of a flame, a response time similar to that of the bimetallic and thermoelectric devices. This is not important in domestic appliances with low gas consumptions, but is a serious fault in large industrial plant where vast volumes of unburnt gas could be liberated in this period. Thus industrial appliances have mainly been the province of electronic F.F.D's which are much quicker in response. (10)

3.1.3 Limited Life

The comparatively short life has proved to be a serious problem when mercury F.F.D.'s are used to sense standing pilots. The constant presence of hot mercury results in dissolution and deposition of metal from the phial walls (see section 4.2.1) causing blockage of the capillary tubing. It is this fault which has limited the use of mercury flame switches in domestic central heating systems, where otherwise they would be an ideal flame monitoring system.

3.2 The Gas Cooker Application

The ovens in British gas cookers normally have maximum gas consumptions of less than 0.3 cu. metres per hour (using natural gas), slow F.F.D. response is not a great problem, and standing pilots are not used. Therefore the mercury F.F.D. has proved to be ideal for this application and in 1977 69% of British cookers were fitted with mercury F.F.D.'s (24). In fact in Britain, gas cookers form virtually the only market for mercury F.F.D.'s, with only insignificant quantities being sold for other applications.

Because of the importance of the cooker market, the application of mercury F.F.D.'s in gas oven control systems will now be considered in detail. Two basic systems are used, the bypass type and the non-bypass type.

3.2.1 Bypass Type Mercury Systems

A typical installation of a bypass mercury F.F.D. is shown schematically in fig. 7, this system being used in the simplest and cheapest of gas cookers. The thermostat has a dual role as it also incorporates a shut-off valve, thus when the thermostat is turned on it allows gas to flow to the F.F.D.. Since the flame sensing bulb is normally cool when starting up no gas would ordinarily flow through the device. A bypass orifice is therefore fitted to the F.F.D. to permit a given flow rate of gas to pass through to the burner whilst the valve is shut. In the United Kingdom these bypass rates must be not greater than 600 W equivalent gas rate (25), although in other countries such as the U.S.A. much lower values are insisted upon. In this way gas passes to the main burner at the bypass rate, and is ignited by either a spark, or in some cases a hot wire. Before 1976 standing pilots were often used to give the ignition, but are not now permitted by British Gas. The bypass gas produces a small bead of flame on the main burner which heats the flame sensing phial and after a delay of 30 to 60 seconds the flame failure device opens. This allows the full gas flow to pass to the burner and the flame to increase to full size. The oven then heats up until the thermostat is satisfied, when it gradually cuts back the gas flow to a maintenance rate determined by a bypass orifice within the thermostat. If in this reduced flame condition the burner should blow out, the flame sensing phial would cool and the F.F.D. would shut. Thus the full flow of gas to the burner is prevented, although gas will always pass to the burner at the F.F.D. bypass rate.

For more expensive cookers the system just described is usually extended further by adding a timer, as shown in fig. 7. When the cooking cycle is to start, the timer turns on the gas supply to the F.F.D., and activates the spark igniter. The system then operates as described above, until the timer shuts off the gas supply at the end of the cooking cycle.

3.2.2 Non-Bypass Mercury F.F.D. systems

These systems tend to be more costly and so are confined to more expensive cookers. The problem with the bypass system is that a large amount of bypass gas is needed to produce a big enough flame on the main burner to open the F.F.D., so if the flame should extinguish unburnt gas will flow into the atmosphere at a high rate. A means of overcoming this difficulty is shown in fig. 8. In this case when the thermostat is turned on gas can reach the F.F.D., but can go no further, since a bypass orifice is not fitted. Gas is also permitted to flow to a timer controlled valve. When the cooking cycle is to start the timer opens this valve permitting gas to flow to the pilot, which is then ignited by a spark generator also turned on by the timer. The pilot heats the sensing phial and the F.F.D. opens, allowing gas to pass to the main burner which is ignited by the pilot. The thermostat controls the main burner until the timer cuts off the gas supply to the pilot. The F.F.D. then closes as the sensing phial is no longer heated, and the main burner is extinguished. For purely manual operation the timer can be over ridden, so that the gas way from the thermostat to the pilot is permanently open, and control of the spark igniter is passed to the thermostat.

A pilot is a much more efficient way of heating the flame sensor, as far less gas is needed than in the bypass/main burner arrangement. If the pilot flame should be extinguished during the operating cycle, only the low gas flow from the pilot escapes once the F.F.D. has closed. Thus this system is much safer than the bypass system. Another advantage of using this system is that the main burner can be throttled back to very low flame levels, by the thermostat without affecting the F.F.D. This enables very low oven emperatures to be properly controlled by the thermostat. In fact the thermostat could turn the main burner off completely, as the pilot would re-ignite the gas when the thermostat reinstated the flow. This mode of operation is commonplace in the U.S.A. but is not the practice in the U.K., where a thermostat bypass is always provided. There are two reasons for this, one being that the extinguishing, and re-ignition of the main burner would cause an annoying 'pop' every so often. The other reason is that British cookers are unique in that the user can see the main burner, and this could deceive the operator if the main burner was seen to be extinguished.

Because the non-bypass system needs a pilot and its associated piping, it is more expensive than the bypass system. Another cost increasing factor is that the F.F.D. must be made to a higher specification to comply with BS 5258 (25). This states that when a F.F.D. is required to prevent the flow of gas under normal operating conditions, the let by in the closed condition must not exceed 85 cm^3/hr when tested with air, in the manner described in the standard. For F.F.D.s only required to prevent flow under conditions of flame failure (as in the bypass system) the requirement is for a maximum let by of 3,000 cm^3/hr. Clearly, making a valve, and testing it to this higher standard, will add to its price.

CHAPTER 4

PROBLEMS WITH MERCURY F.F.D.'S

4.1 Mercury Health Hazard

In recent years the public have become much more aware of the existence of poisons in the every day environment. In particular, mercury has earned itself a bad name, due partially to the famous incident of mercury poisoning at Minamata in Japan (26). However this incident involved the extremely poisonous alkyl mercury compounds and not the far less toxic mercury metal. The public unfortunately is unlikely to be aware of this distinction and the prospect of a possible 'mercury scare' has caused much worry in the gas industry.

Undoubtedly the symptoms of metallic mercury poisoning are very worrying. Bidstrup (26) lists the classical symptoms as including, "gingivitis and stomatitis, accompanied by excessive salivation or a metallic taste, erethism and tremor". Also listed are various non-specific symptoms and signs such as "weakness, unusual fatigue, loss of weight, pallor and disturbances of the gastro intestinal function." The tremor can be sufficient to make operations such as writing or drinking from a cup very difficult. In serious cases kidney damage can occur, which in rare instances has led to death. The sensitivity of individuals to mercury poisoning seems to vary, and in particular young children below the age of 4 years can be very sensitive, developing an illness called 'pink disease' from low exposures.

Mercury gains access to the body mainly through the respiratory tract, but can also be absorbed through the skin or by ingestion. Thus mercury contaminated air is one of the main causes of the illness. Bidstrup states that the accepted threshold limit is 0.1 mg per cu. metre of air, and at room temperature air saturated with mercury vapour contains 10 mg per cu. metre. Goldwater (27) has pointed out that spilt mercury tends to break into tiny droplets with a vast increase in surface area giving a high evaporation rate. Spilt mercury is notoriously difficult to clean up as it does not wet most surfaces, and forms small mobile droplets. Attempts to remove these make them roll away and enter small holes and cracks, from where they continue to contribute to the mercury burden in the air, but cannot be removed.

Mercury F.F.D. thermal systems (the capsule, capillary and phial) have been known to develop leaks in service, usually because of a capsule failure, or a crack in the phial (see table 3). A capsule leak, providing the valve failed shut, and no mercury found its way into the burner assembly and its piping, would not be a great problem as the mercury would collect in the valve body and be removed when the F.F.D. was replaced. A phial leak is much more serious as mercury would be spilt into the bottom of the oven, which could well be at high temperature. Any attempt to clean up this spilt mercury would undoubtedly leave traces behind which would gradually evaporate.

However it must be stated that the amount of mercury contained in a F.F.D. is very small, typically less than 1 gram, and that there has never been a case of mercury poisoning of a member of the public which could be attributed to one of these devices. The real worry within the industry is that if the public were to discover that mercury is used in gas cookers, the likelihood of bad publicity could result in loss of sales to electric cookers.

One group of people who are at risk though, are the people involved in the filling of mercury thermal systems. These are filled in trays in a vacuum chamber, and during loading and unloading of these trays the worker comes into contact with mercury. The process uses large quantities of mercury, and occasional accidents can result in mercury spillage. The thermal systems after filling are sealed, a process which involves either T.I.G. welding of the flattened phial end, or the spot welding of a ball into a specially shaped filling hole (see fig. 5). Both processes cause heating of the mercury which results in vapour emission. There are many cases (26) of workers using mercury under similar conditions in other industries developing mercury poisoning symptoms, and the occurrence of such incidents cannot be ruled out in this industry. An awareness of such a danger has led to regular medical checks for all workers at Harper Wyman Ltd. who come into contact with mercury.

4.2 Reliability

Table 3 presents mercury F.F.D. field failure data for the period up to March 1977, (28) which together with laboratory test data published by Wharf (29) and reproduced in table 4, suggests that mercury F.F.D. reliability is not what it should be. This is especially bad when one considers that the conditions for a mercury F.F.D. fitted in a cooker is not particularly arduous. British Gas (29) assume for the purposes of reliability estimation a design life of ten years, during which only 3,000 cycles will be completed. Tables 3 and 4 show that there are 3 major failure modes specific to the mercury F.F.D., which between them account for most failures in service. They are:-

(1) blockage due to phial leaching
(2) capsule failure
(3) phial leakage.

These are examined in detail below.

4.2.1 Blockage and Phial Leaching

A phial material must be able to contain hot mercury, and resist an external oxidising environment. For this latter reason the choice of materials is limited in practice to stainless steels. Fig. 9 taken from Weeks work (30) shows the solubilities of various metals in hot mercury. It will be seen that nickel has a high solubility, and for this reason British F.F.D. manufacturers have avoided austenitic steels and used ferritic stainless steels, either of A.I.S.I. type 446 or 430 for the phial. However as fig. 9 shows both chromium and iron have appreciable solubility in mercury, and this has given rise to problems in F.F.D.'s subjected to long service. Fig. 10 shows the internal surface of a phial which has been in use. The deposited material on the inner surface can be seen quite clearly. This material if deposited in the capillary could cause blockage, a possibility which has been found to be happening in practice. British Gas (31) report of a device which had completed 7,800 hot/cold cycles on a test rig and had become very slow in operation. The phial was sectioned and examined. Iron deposited from solution in the mercury was found all over the inner surface, and regions of chromium deposition were found, which were thought to have caused a blockage resulting in the slow operation.

The mechanism which has been suggested (32) for the attack on the phial, and precipitation of material is as follows: At the running temperature a stable liquid-vapour interface (there can be two interfaces) forms at a point in the phial which is determined by the temperature gradients existing within the phial, and its inclination. At this surface mercury laden with solutes is continually boiling, and hence the solutes are precipitated here. Above the interface mercury vapour condenses on the cool parts of the phial. Weeks (30) states that the erosion rate of a metal in mercury is proportional to:-

$$S_o - S_i$$

Where S_o is the metal solubility and S_i is the concentration of the metal already in solution. For newly condensed mercury S_i is clearly zero, thus erosion rates will be proportional to S_o, values of which are indicated by fig. 9.

The temperature at which this solvent attack takes place is the boiling point of mercury at that particular pressure. (See fig. 9). Thus as the capsule stiffness increases, the erosion and deposition rate also increases, as the solubilities increase with temperature. (See fig. 9). Therefore this problem could be reduced by using more flexible capsules. Another suggested solution (33) was to reduce the amount of chromium in the steel, or use an iron phial with a chromized exterior. A typical F.F.D. (Harper Wyman type 5920) operates at a pressure of around 830 kPa at which the boiling point of mercury is 510 ^{o}C. Reference to fig. 9 will show that at this temperature the difference in solubilities between iron and chromium is small, and a reduction in operating pressure would probably result in iron being more soluble than chromium. Thus even the use of pure iron phials would not offer a solution to the problem. Another conceivable answer would have been the use of a wide bore capillary tube, thereby making blockage an unlikely event, but as these devices need a restriction in the system to function correctly, this is not possible. Explosive boiling of the mercury has always been a problem (Cobb (15) noted this) because of the violent pressure fluctuations it causes in the thermal system, resulting in rapid variations in the capsule deflection, which produces unstable valve openings, creates noise, and in severe cases could cause early fatigue of the capsule. To avoid this happening it is usual to place a restrictor in the system to damp out these pressure fluctuations. The restriction is either a very narrow capillary, or a capillary flattened slightly at one point. In some cases a metal 'slug' is placed in the phial which also acts as a restrictor. As workable devices always need some form of restriction the danger of blockage is always high. Even if the restrictor is remote from the phial there is always a danger of loose particles of deposited material being carried to the restrictor and causing blockage.

Hence in any mercury device subjected to long use, blockage due to phial material deposition will be a problem, and it is for this reason that mercury F.F.D.'s cannot be used to sense standing pilots. The only way to alleviate the problem is to fit a more flexible capsule, and to try to arrange for the liquid vapour interface to be at a place in the phial such that any deposition of material occurs where it cannot cause a blockage. Even so it is doubtful if a mercury device could be made sufficiently reliable to sense a standing pilot.

4.2.2 Capsule Failure

Capsule failure would appear to be a relatively common occurrence. British Gas field failure data (table 3) has shown that up to 1977, 4.5% of all mercury F.F.D.'s would fail in this way during their 10 year life. Wharf (29) reports of experimental work done at Watson House (see table 4), in which 230 mercury F.F.D.'s were subjected to a 7½ minute hot, 7½ minute cold cycling. It was found that of a total of 19 failures, 12 were due to "bellows rupture".

Cracking of the capsule is caused by fatigue due to the repeated flexing of the capsule. However a 3,000 cycle life is not long in terms of fatigue, and failures within this lifetime are due to a mixture of bad design and poor manufacture. Bad design is a major element in these failures, as in many current designs the very high capsule "strokes" produced when the phial is heated result in very high cyclic stresses which lead to a low cycle life. Also in some designs the welds fixing the upper and lower bosses to the diaphragms can act as stress raisers, lowering the fatigue life. Poor manufacture includes such faults as bad diaphragm edge welding, poor top and bottom boss welds, poor material, and marks on the diaphragms which act as stress raisers.

It is also possible that mercury attack reduces the fatigue life of the 302 stainless steel capsules. The reduction in fatigue life is very pronounced in brasses and some aluminium alloys (34) but seems to be less so with stainless steel. Rostoker et al (34) report only a slight reduction in the fatigue life of 17-7 PH steel when wetted with mercury. For any effect at all to be produced the mercury must wet the capsule surface, which entails removal of the extremely tough oxide layer on the stainless steel. Abrasion effects are a usual cause of such a happening, and it is conceivable that friction between the two nesting capsules, as they move relative to one another could cause oxide removal.

Table 4 shows that a significant percentage of capsules develop a permanent set. This is a potentially dangerous failure mode as it can result in the valve being held permanently open. The problem is caused by the very high stresses mentioned above, and where capsules developed permanent set the stresses were sufficiently high to take the material past its yield stress. Again this is a design problem, but it is compounded by the choice of 302 stainless steel for the diaphragms, a material which can only be hardened by the work done in forming the diaphragms, and thus is restricted to quite low yield stresses ($\sim$900 MPa).

4.2.3 Phial Cracking

It was indicated in section 4.2.1 that the need to keep phial leaching down to a minimum had dictated the use of ferritic stainless steels of A.I.S.I. type 446 (16-18% Cr), or 430 (23-27% Cr). These materials can suffer from embrittlement after extended service at high temperatures. Three embrittlement mechanisms are responsible:-

(a) '475 ^{o}C' embrittlement due to the precipitation of a chromium rich (α prime) phase (35). This causes an increase in hardness and a reduction in izod impact energy. The maximum hardness increase is noted at 475 ^{o}C (hence the name), and is made greater by increasing the chromium concentration. Generally steels containing less than 15% chromium do not exhibit this effect.

(b) Sigma phase embrittlement. This phase forms at temperatures above 500 ^{o}C (35), precipitating first at the grain boundaries. The presence of the sigma phase increases hardness and reduces notch toughness. The problem is encountered with steels containing more than 15 to 20% chromium.

(c) Mercury embrittlement. It was noted in section 4.2.2 that mercury can reduce the fatigue life of metals. An allied problem is the mercury embrittlement of metals, in which mercury attack reduces the failure stress to below the yield point resulting in brittle failure. This is caused by intergranular attack on the metal by the mercury, which produces cracks which propagate easily. Mercury embrittlement is contingent on the mercury penetrating the surface oxide of the metal, which in the case of F.F.D. phials is known to be happening due to the solution attack. This phenomenon is well known in brasses and aluminium alloys, but Rostoker et al (34) report no embrittlement of mild steel at 30 ^{o}C by mercury. However the mercury in a F.F.D. phial is at high temperature (approx. 500 ^{o}C) for long periods, and thus a slow embrittlement process cannot be ruled out. British Gas (31) in their examination of a used mercury F.F.D. found a region of subsurface attack on the inside of the phial where once the surface had been penetrated, usually along a grain boundary, attack proceeded along well defined regions, one or two grains from the surface. This could possibly have been an early stage of a slow mercury embrittlement process.

A phial's operating conditions may be such that the hottest point is at around 800 ^{o} C, thus exposing the steel to a range of temperatures from this high value down to room temperature. Both 475 ^{o} C, and sigma phase embrittlement are therefore possible, combined with mercury embrittlement, and thus it is not surprising that severe embrittlement has been found in practice. Tests (36) have shown that embrittled phials could be broken by hand force, and thus impacts due to servicing or cleaning the cooker could easily cause breakage, as is evidenced by the 5% of mercury F.F.D.'s returned to British Gas with signs of phial cracking (table 3).

Table 3 shows that 0.4% of returned F.F.D.'s had leaked from the phial closure weld. Such failures occur with designs which are filled from the phial end and are then flattened and sealed by T.I.G. welding. Mercury if present in the weld area can evaporate producing bubbles in the weld which lead to early failure.

CHAPTER 5

THE FEASIBILITY AND MODELLING OF AN ALTERNATIVE F.F.D.

5.1 Features required by a new F.F.D.

In Chapter 4 the problems concerning the mercury F.F.D. were outlined. Two problems were fundamental, the fact that the devices contained toxic mercury meant that a leak must always be regarded as a serious occurrence, and the attack on the stainless steel phial by the mercury limited the life of the component. Design modifications did not appear sufficient to solve these problems, and a new approach was needed. Any new device under consideration must be able to replace the mercury F.F.D. in its present day uses, (see chapter 3) and if possible it should be applicable to a wider variety of appliances. To replace the mercury F.F.D. any new device must satisfy the following requirements:-

(a) It must be cheap to make.
(b) It must be self contained and not need an electricity supply.
(c) It must open and shut automatically.
(d) It must have a flexible connection between the sensor and valve.

In order to be suitable for a wider range of appliances than the mercury F.F.D., any new device should also satisfy some of the following requirements:-

(e) It must be able to sense standing pilots without premature breakdown.
(f) It must have a high cycle life.
(g) It should have a high gas flow capability, if possible up to 3 cubic metres per hour at 0.75 mb pressure differential.
(h) It should have a faster response time than that of bimetallic, thermoelectric or mercury devices.

Reference to table 2, which reviews mechanical flame detection methods, will show that none of the devices known at present will adequately substitute for the mercury device in requirements (a) to (d) listed above. Hence there is a call for a completely new device which will satisfy requirements (a) to (d) and if possible have some of the desirable features (e) to (h) to give a wider market appeal than the mercury valve.

Besides meeting these market orientated requirements, any new type of F.F.D. must of necessity comply with the relevant British Standards. The most important of these is BS 6047 part 1 (13) issued in 1981 which covers "Flame supervision devices for domestic, commercial and catering gas appliances", part 1 being the "Specification for heat sensitive type". The fundamental requirements laid down by this document are as follows:-

1) The device must be fail safe, and cause no danger to persons or the surroundings.
2) It must operate correctly over its full range of nominal working pressure, and an ambient temperature range of 0 to 60 $^{\circ}C$, or wider limits if claimed by the manufacturer.
3) When air pressure of 1.5 times the maximum pressure declared by the manufacturer (but at least 50 mb for 2nd family gas devices, or at least 60 mb for 3rd family gas devices), is applied to the inlet connection of a closed F.F.D. (with the bypass blanked off if necessary) the let by should not exceed the following values:-

Nominal size R (inches)	Nominal size DN (mm)	cm^3/hr air
$<\frac{3}{8}$	<10	20
$\frac{3}{8}$ to 1	10 to 25	40

4) The F.F.D. should operate satisfactorily, or the valve of the device should be closed and remain closed after the flame sensor, as defined by the manufacturer, has been maintained at 1000 $^{o}C \pm 50$ ^{o}C for 4 hours. Overheating may result in failure, but not failure to shut down, and rupture of the flame sensing element must cause closure of the F.F.D.

5) The F.F.D. must be capable of performing 6,000 operations without failure. For this test the first 1,000 cycles must be at 60 ^{o}C (or higher if claimed by the manufacturer), followed by 1,000 cycles at 0 ^{o}C (or lower if claimed by the manufacturer), and finally the last 4,000 cycles must be completed at 25 $^{o}C \pm 5$ ^{o}C.

Further specifications for F.F.D.'s are set out in BS 5258 parts 1 to 12 (25) "Safety of Domestic Gas Appliances". Each part of this specification covers one type of appliance and states whether a F.F.D. is required and gives the maximum opening and closing times permitted for the F.F.D. These details are summarised in table 5.

In considering a new type of F.F.D. it is important to take cognisance of the range of expertise available to the F.F.D. manufacturing industry. Cooper (37, 38) in his "Project NewProd" looked into the factors affecting the success of new industrial products. He found that amongst other factors, "technical and production synergy-proficiency" was an important determinant of new product success. Thus to design a new type of F.F.D. whose concepts and production technology were not within the experience of the industry would be to invite failure of the new product. Therefore it is worth considering a device similar to the mercury F.F.D., but filled with some non-toxic fluid. Such a device would very likely fulfil requirements (a) to (d) (above), and if in addition some of requirements

(e) to (h) were also fulfilled, a broadening of the market for this type of F.F.D. would be possible.

5.2 A New Filling Fluid for Thermal Systems

The opening temperature of a F.F.D. must be such that at any ambient temperature likely to be encountered in an oven (or other appliance), the opening and closing times are less than those specified by BS 5258 (table 5). The optimum opening temperature will vary between appliances, depending on the range of ambient temperatures experienced by the F.F.D. and the running temperature of the flame sensor, but for most appliances the optimum F.F.D. opening temperature would be in the range of 200 °C to 400 °C.

Mercury boils at 1 atmosphere pressure (101.3 kPa) at 357 °C and generally needs to be heated to approximately 400 °C to develop sufficient pressure (~100 kPa gauge) to operate a F.F.D.. However in some cooker applications this 400 °C opening temperature has proved to be rather too high, as the small bypass flame has difficulty in heating the phial sufficiently to give a reliable valve opening. Thus it would seem that the choice of a lower boiling point liquid might be advantageous and when the application demanded it, the opening temperature of the F.F.D. could be increased by raising the working pressure. Water for instance boils at 100 °C, but this temperature could be raised by increasing the operating pressures. For a temperature of 200 °C the saturated vapour pressure would be 1.55 MPa, at 300 °C it would be 8.58 MPa, at 350 °C it would be 16.52 MPa and 400 °C is beyond the critical point of water (39). Clearly in extending the opening temperature much above the normal boiling point the high pressures present design problems. The same would apply to other liquids, as the increase in vapour pressure with temperature is always very rapid. A simplified form of the Clausius-Clapeyron equation, which applies if the pressures are not too high and the temperature is not too near the critical point, illustrates how the rate of increase of vapour pressure varies with temperature:-

$$\frac{dP}{dT} = \frac{LP}{RT^2} \qquad \text{....... (5.1)}$$

where P is the vapour pressure, T is the temperature, R is the gas constant and L is the Latent heat of vaporization, which is a function of T tending towards zero at the critical temperature. For small temperature intervals some way below the critical temperature, L can be assumed to be a constant (40). Integrating this equation gives the following approximate relationship:-

$$P = Po \exp \left(\frac{-L}{RT}\right) \qquad \text{....... (5.2)}$$

showing an exponential dependence of vapour pressure on temperature.

Therefore low boiling point liquids such as water and ethanol cannot be used and a liquid with a boiling point of around 300 °C should be chosen, enabling a F.F.D. to be constructed with an operating temperature variable over the range 300 °C to 400 °C. In searching for such a liquid, two problems were encountered. Firstly the liquid must not solidify at normal temperatures (say down to -10 °C) as this would prevent the device from working. Secondly the chosen fluid must be able to withstand very high temperatures, as phials can reach 800 °C when operating, and in order to meet the requirements of BS 6047 part 1, the filling fluid must be capable of withstanding 1,000 °C ± 50 °C for 4 hours. Liquid metals other than mercury are available, such as sodium-potassium alloys and caesium-sodium-potassium alloys which have melting points below 0 °C, but unfortunately their boiling points are higher than mercury (e.g. 78% K-Na alloy boiling point 667 ^{o}C, melting point -12 ^{o}C). These alloys would be very dangerous to use, because of their explosive combustion in air when hot, and would attack the phial over a long period in the same way as mercury. Many compounds, both organic and inorganic have boiling points at around 300 ^{o}C, but nearly all will decompose at the high temperatures encountered in the F.F.D. phial. Any tendency for the fill fluid to decompose and liberate gaseous decomposition products would be most dangerous and contrary to BS 6047 as the F.F.D. thermal system (the phial, capillary and capsule) could become pressurized, causing the valve to remain in a permanently open condition. As the filling fluid must withstand very high temperatures for a long period (greater than 3,000 hours), and also be able to tolerate a 1,000 ^{o}C test for 4 hours and always fail safe, the use of these compounds as a filling fluid is effectively ruled out.

A further possibility considered was the use of a reversible reaction which would liberate gas at a certain temperature. The choice of compound need not be a liquid, as a solid substance could be packed into the phial. This concept has been used in refrigerator thermostats (41), where activated charcoal liberates or adsorbs nitrogen or carbon dioxide gas at a certain temperature. However such adsorption processes are essentially a low temperature phenomenon, and for a high temperature device a reversible chemical reaction would have to be used. Such a reaction would by definition liberate a fairly reactive gas, which would gradually react with the hot stainless steel phial. This would reduce the pressure in the device, resulting in its eventual failure.

The obvious attraction of using an elemental gas made it a first contender for investigation as a filling fluid for F.F.D. thermal systems. Such a gas would not suffer from decomposition at high temperatures and an inert gas would eliminate attack on the thermal system. The limitation with a gas fill was that it would not exhibit the high pressure changes with rises in temperature shown by substances undergoing a phase change, since the pressure of a gas at constant volume is proportional to the absolute temperature. This limitation could well be overcome by the large temperature changes which a F.F.D. senses. As an example the ambient temperature in an oven may be 200 ^{o}C and the phial running temperature could be 700 ^{o}C. This would mean that a 500 ^{o}C temperature rise was available to operate the valve, which would be equivalent to doubling the fill gas pressure at constant volume. Of course in a workable device, the pressure rise would be less than this as the thermal system would have to do work in moving the gas valve. Such a device, due to the steady rise in gas pressure with temperature would have the advantage over the mercury F.F.D. that it could be calibrated to open at any temperature within the range of interest, i.e. 200 ^{o}C to 400 ^{o}C.

In principle therefore, it would seem that a gas filled device could substitute for the mercury F.F.D., and also have some useful advantages over it. The question which requires an answer, however, is would a gas filled thermal system have a sufficiently good performance to operate a F.F.D.? The following sections examine the theory of gas filled thermal systems to enable performance predictions to be made.

5.3 Model of Gas Filled Thermal Systems

To predict how a gas filled thermal system will perform, a simplified model is needed. A drawing of the proposed model is shown in Fig. 11. This consists of a phial of volume V_p, connected via a capillary to a capsule of volume V_c.

As the pressure P (kPa absolute) in the thermal system varies, the capsule extension b will vary also. The capsule internal volume (V_c) is related to b, and for the purposes of this model this relationship will be defined as:-

$$V_c = \pi r^2 bS \qquad \ldots\ldots\ (5.3)$$

where r is the capsule's active radius, and S is a constant. For capsules whose surfaces deform conically when they are pressurized S would be ⅓, whereas for capsules whose surfaces undergo a spherical deformation it can be shown that for small values of b, S would be ½. In fact this equation agrees quite closely with experiment and corrugated diaphragms have been found to have values of S close to ½. (See Newell (42) and section 7.6)

However equation (5.3) does show that when b is zero, V_c will also be zero, but in reality all capsules, even "nesting" capsules, have some residual volume at zero extension. This residual "dead volume" will tend to reduce the performance of the thermal system, as will the volume inside the capillary tube. Thus, for the purposes of this model, the residual capsule volume and the capillary volume will be combined to give a total "dead volume" U.

When manufactured the thermal system will be filled to a pre-determined pressure. In the present work the "fill pressure", P_f (kPa absolute), will be defined as the pressure inside the thermal system when it is at 300 ^{o}K, and when the capsule is in its normal unloaded state. To enable performance calculations to be made for a thermal system, a reference value for the amount of gas contained within the system is needed. A convenient measurement of this is what shall be called the "Nominal Fill Pressure" P_n (kPa absolute) which is defined as the pressure within the thermal system when it is at 300 ^{o}K and when V_c is zero. For thermal systems which are filled to pressures less than or equal to atmospheric, P_n will be equal to P_f, but for those with fill pressures greater than atmospheric, P_n will be a purely calculated quantity, related to the "fill pressure" by the following equation:-

$$P_n = \frac{P_f\ (V_{co} + U + V_p)}{(U + V_p)} \qquad \ldots\ldots\ (5.4)$$

where V_{co} is the volume within the capsule at the fill temperature and pressure.

When the phial is heated to a temperature of T ^{o}K, the gas within it expands, thereby increasing the pressure of the whole thermal system. For the purposes of the model it is assumed that only the gas in the phial is at T ^{o}K and that all of the gas in the rest of the system is at the environmental temperature T_e ^{o}K. As the pressure P in the system rises the capsule extension b will increase. As a first approximation the capsule extension can be assumed to be proportional to the pressure, giving the following relationship:-

$$b = X.\ (P - P_a - P_s) \qquad \ldots\ldots\ (5.5)$$

where X is the pressure sensitivity of the capsule and P_a is the atmospheric pressure. Some capsules will not start to deflect until a certain pressure has been exceeded, and this "starting pressure" is represented by P_s in equation (5.5). Certain capsule designs (see section 7.2) come quite close to this ideal linear behaviour, but more frequently (see also section 7.2) X is a function of b which decreases quite rapidly as b increases. For capsules exhibiting a low nonlinearity, an average pressure sensitivity $\bar{X}$ can be calculated and used in equation (5.5) to give a reasonable approximation to the experimental performance. However for more non-linear capsules, the actual pressure-extension data must be used in any performance calculation in order to obtain predictions.

5.3.1 Variation of Capsule Deflection with Phial Temperature

As stated in the last section the gas within the phial is assumed to be at T ^oK and the rest of the gas in the thermal system is assumed to at T_e ^oK. To calculate the pressures developed within the system when the phial is heated, an average temperature T_{ave} must be assigned to the gas in the thermal system.

From the gas laws, the masses of gas in each of the three parts of the system are:

$$M_p = \frac{P\ V_p}{R\ T} \qquad \text{.......} \ (5.6)$$

$$M_u = \frac{P\ U}{R\ T_e} \qquad \text{.......} \ (5.7)$$

$$M_c = \frac{P\ V_c}{R\ T_e} \qquad \text{.......} \ (5.8)$$

where M_p, M_u, and M_c are the masses of gas in the phial, dead volume and capsule respectively. The average gas temperature will be given by:

$$T_{ave} = \frac{M_p\ T + T_e\ M_u + T_e\ M_c}{M_p + M_u + M_c} \qquad \text{.......} \ (5.9)$$

Substituting (5.6), (5.7) and (5.8) in (5.9) gives:-

$$T_{ave} = \frac{T\ T_e\ (V_p + U + V_c)}{V_p\ T_e + T\ (U + V_c)} \qquad \ldots\ldots\ (5.10)$$

Now that an expression for T_{ave} has been obtained, P, the system pressure can be calculated from the gas laws:-

$$P = \frac{P_n\ (V_p + U)\ T_{ave}}{300\ (V_p + U + V_c)} \qquad \ldots\ldots\ (5.11)$$

where P_n, the nominal fill pressure, is the pressure when the entire system is at 300 ^oK, and when V_c is reduced to zero. From (5.10) and (5.11):-

$$P = \frac{P_n\ T\ T_e\ (V_p + U)}{300\ [V_p\ T_e + T\ (U + V_c)]} \qquad \ldots\ldots\ (5.12)$$

When considering thermal systems with capsules whose performance is linear, a relationship between b and T can be obtained as follows:-

from (5.5)

$$b = X\ P - X\ (P_a + P_s) \qquad \ldots\ldots\ (5.13)$$

Substituting (5.12) into (5.13) gives:-

$$b = \frac{X\ P_n\ T\ T_e\ (V_p + U)}{300\ [V_p\ T_e + T\ (U + V_c)]} - X\ (P_a + P_s) \qquad \ldots\ldots\ (5.14)$$

For non-linear capsules, the actual pressure-extension function must be found experimentally, and combined with equation (5.12) to give a relationship between b and T.

5.3.2 The Thermal System as part of a Valve

When incorporated into a valve the thermal system is arranged such that at a certain phial temperature T_s, the capsule just starts to lift the valve plate off its seat allowing the gas to flow. With a further rise in phial temperature the valve lift h will increase according to the equation:-

$$h = b(T) - b(T_s) \qquad \ldots\ldots\ (5.15)$$

where $b(T)$ and $b(T_s)$ are the values of b calculated from (5.14) at temperatures T and T_s respectively.

5.3.3 Variation of T_s with Atmospheric Pressure and Environmental Temperature

At the temperature T_s, at which the valve just starts to open, equation (5.12) becomes:-

$$P = \frac{P_n\ T_s\ T_e\ (V_p + U)}{300\ [V_p\ T_e + T_s\ (U + V_c)]} \qquad \ldots\ldots\ (5.16)$$

Rearranging (5.16) gives T_s as a function of P:-

$$T_s = \frac{300\ P\ V_p\ T_e}{P_n\ T_e\ (V_p + U) - 300\ P\ (U + V_c)} \qquad \ldots\ldots\ (5.17)$$

The valve will just start to open when the extension of the capsule exceeds a certain value, at which the differential pressure existing between the inside and outside of the capsule is always constant. Thus if the valve is set to open when the internal pressure inside the thermal system is P_i, and the atmospheric pressure changes by an amount ΔP_a, then the valve will open at a different internal pressure $(P_i + \Delta P_a)$. Because of this T_s will change to a new value given by the following equation:-

$$T_s = \frac{300\, V_p\, T_e\, (P_i + \Delta P_a)}{P_n\, T_e\, (V_p + U) - 300\, (U + V_c)\, (P_i + \Delta P_a)} \quad \ldots\ldots (5.18)$$

Equation (5.18) also shows how a combined change in atmospheric pressure ΔP_a and ambient temperature T_e will affect the opening temperature T_s. From this equation, the maximum range of ambient conditions can be determined, for which a given design of valve would be suitable, providing the maximum and minimum value of T_s has been decided, then equation (5.18) can be solved to find the limits to which ΔP_a and T_e can be taken both individually and together.

5.3.4 The Effect of Springs

In designs of F.F.D. where the valve plate is normally held shut by a spring, the capsule will have to overcome the spring force in order to open the valve. Since the movement of valve plates will be very small (~ .25 mm, see chapter 8) and as the springs used in a F.F.D. normally have a fairly low rate, the spring force (F) can be taken as constant. This spring force will increase the capsule starting pressure (P_s) to a new value given by:-

$$P_s = P_{si} + \frac{F}{A_e} \quad \ldots\ldots\ldots (5.19)$$

where P_{si} is the intrinsic starting pressure of the capsule and A_e is the pressure effective area, which is defined by:-

$$A_e = \left(\frac{\partial F}{\partial P}\right)_b \quad \ldots\ldots\ldots (5.20)$$

where F is the capsule force output caused by a pressure P. Normally A_e remains reasonably constant throughout the deflection and pressure range of the capsule, and generally has a value of around 40% of the active capsule area (42). Having calculated the modified value of P_s, the performance of a spring loaded F.F.D. can be worked out as before.

5.4 Computer Programs

Computer programs were developed from the model discussed in section 5.3 to enable performance predictions to be made for gas filled thermal systems. The BASIC language was chosen for these programs, as this is the most common language in use on the "mini computers" most likely to be available to smaller manufacturing companies.

Two programs were developed; ffd.basic (see appendix 1) which calculates the performance of a given system, and var.basic (see appendix 3), which computes the effect of ambient temperature and pressure changes on a thermal system. These programs are described briefly below.

Figures 53 to 59 show performance predictions produced by the programs. These predictions and the assumptions underlying them are discussed fully in chapter 8.

5.4.1 ffd.basic

This program reads in capsule pressure-extension data from a named file specified by the operator. The data file must contain a series of points:-

$(0,0)$, (P_1, e_1), ... (P_m, e_m)

where e_m is the capsule extension (mm) at a given pressure P_m (kPa). For a linear capsule only two points need be supplied $(0,0)$ and (P_1, e_1), the first being the start and the second marking the end of the pressure-extension locus. This data is read into a matrix h (lines 400 to 510) by the program and the pressure calculation subroutine (lines 1200 to 1430) uses this data to calculate the pressure z, at any extension b, by means of a linear interpolation. For non-linear capsules, the pressure-extension data file must contain more experimental points and provision is made for up to 40 data points. The program uses this data to approximate the true pressure-extension curve to a series of short straight lines, therefore the more data points read into the program, the more accurate its predictions will be.

The thermal system parameters are then input by the operator:- phial volume (v mm^3), capsule radius (r mm), fill pressure (p kPa absolute), dead volume (u mm^3) and finally start pressure (o kPa) (lines 270 and 280). The program computes the nominal fill pressure (lines 520 to 730) and then goes on to compute the total capsule extension and stroke at phial temperatures of 27 ^oC, 50 ^oC and then at 50 ^oC intervals up to 800 ^oC (lines 760 to 1100). This is done using an iterative process at each phial temperature by first of all computing the pressure (w) in the thermal system (lines 1210 to 1260) at zero capsule extension (b) and comparing this to the pressure (z) at zero extension calculated from the pressure extension data contained in matrix h. The capsule extension (b) is then increased in 0.1 mm steps until z is greater than w, when b is reduced in 0.01 mm steps until z is less than w. The program then increases b in 0.001 mm steps until z becomes greater than or equal to w, and the value of b is then taken as the value of the capsule extension at this particular phial temperature. This iterative operation is repeated at each phial temperature, and the computed performance data is placed in a file "output" (see appendix 2 for a typical example), which can be printed out if a copy is needed. Computed data is also placed in a file "file31", which can be used in conjunction with a graph plotting program to give a direct graphical output. (See fig. 29 for an example).

5.4.2 var.basic

This program is based on ffd.basic and operates in essentially the same way. Pressure extension data is taken from a specified file and stored in the data matrix h (lines 470 - 580), then as before the operator inputs phial volume, capsule radius, fill pressure, dead volume, and start pressure (lines 240 and 250). For var.basic the temperature at which the valve is set to open, T_s degrees C (called t in the program), must also be specified. The program then goes through the iterative proceedure described in 5.4.1 and computes the total capsule extension at the phial temperature T_s for 10 ^{o}C ambient temperature intervals between 0 ^{o}C and 150 ^{o}C (lines 590 - 920). Also calculated is the mean rate of increase of capsule extension with ambient temperature between 0 ^{o}C and 80 ^{o}C, 80 ^{o}C and 150 ^{o}C and over the whole range 0 ^{o}C to 150 ^{o}C (lines 930 - 950).

The opening temperature of a gas filled F.F.D. would normally vary with ambient temperature, therefore the designer might wish to add some form of ambient temperature compensation to a F.F.D.. All the data needed to select the correct temperature compensation has now been computed and having decided on a particular value, the operator inputs this into the program (line 1100). Starting with an ambient temperature of 0 ^{o}C (line 1190) and a phial temperature of T_s + 75 ^{o}C (line 1180). the capsule extension (b1) needed to just open the valve, taking into account the temperature compensation, is then computed (line 1240). The pressure (z) required to give the capsule extension b1 is derived from the pressure-extension data matrix h (lines 1250 - 1370) and the actual internal pressure (z1) at this same extension is calculated using equation 5.16 (line 1410).

z and atmospheric pressure are then subtracted from z1 (line 1420) to give z2, the change in atmospheric pressure needed to produce a valve opening temperature of T_s + 75 ^{o}C at an ambient temperature of 0 ^{o}C. This is repeated for values of ambient temperature from 0 ^{o}C to 140 ^{o}C in 20 ^{o}C steps. The whole process is further repeated for T_s steps of 25 ^{o}C, in the range T_s + 75 ^{o}C to T_s - 100 ^{o}C, giving a total of 64 data sets which are stored in a matrix C (lines 1200 - 1500). All of the computed data is then placed in a file "voutput", which can be printed out if a "hard copy" is required (see appendix 4 for an example). The computed ambient temperature/atmospheric pressure change/T_s data is also placed in a file "file32", which can be used in conjunction with a graph plotting program to give a direct graphical output (see fig. 58 for an example).

CHAPTER 6

THE PROBLEM OF GAS LOSS FROM THERMAL SYSTEMS

6.1 Diffusion through holes

In a study of the feasibility of gas filled thermal systems, the question of leakage is of great importance. The design life of a thermal system must be at least 10 years and as the quantity of gas contained is small (about 500 mm^3), even a small leak will cause the device to fail prematurely. Any hole present in a pressurized thermal system will cause gas to be lost at a rate proportional to the pressure differential across it and varying inversely as the square root of the molecular weight of the gas. Thus production techniques must be sufficiently good to produce a thermal system without any leaks. This is technically quite feasible as exemplified by the production of evacuated aneroid capsules for barometers and altimeters and the manufacture of refrigerant gas filled thermostats for refrigerators (41). In these devices there must be no appreciable ingress or loss of gas over a period of many years, as this would seriously affect their accuracy.

Experience in the vacuum industry has shown that many unavoidable leaks in metal walls are caused by porosity in the steel. This porosity arises when the steel is manufactured, and the forming processes which the steel undergoes influence the direction in which the pores run. Hence in the case of rolled steel strip, the pores would run along the plane of the strip and, except in very bad examples, leakage from one side of the strip to the other would not occur. This also applies to tubing, as the drawing process will make the porosity run in the direction of the tube, thus there will be no leakage from inside to outside. Therefore as the capsule will be formed from stainless steel strip and the capillary and phial will be made from tubing, the thermal systems should have very few intrinsic leaks. The main leakage risk will occur at welded or brazed joints and a good design would reduce the number of these to a minimum.

Inevitably a certain percentage of thermal systems will leak and these must be easily detectable in the production process. One way of doing this would be to use helium, or a mixture of helium and some other gas to fill the thermal system. The sealed thermal system could then be checked for any leaks with a helium mass spectrometer. Commercial helium mass spectrometer leak detectors are capable of detecting leaks as small as 10^{-10} Torr litres per second (43). Thus if for example a thermal system of 500 cu. mm internal volume is filled with pure helium and one assumes that failure has occurred when the gas pressure has reduced by 10 kPa, then the smallest detectable leak would be one which caused failure after 15.6 years. Clearly when viewed in terms of a ten year design life it can be seen that mass spectrometer leak detection offers a sensitive means of inspecting finished thermal systems.

Inspection of every thermal system by mass spectrometer would probably not be feasible on the factory floor. The value of this technique would be in quality control, where say 1% of thermal systems produced are checked. This ought to be adequate, since with mass production techniques, faulty products will tend to come in batches, due to wrong setting of production machinery, etc..

6.2 Gas Loss due to Reaction with the Thermal System Walls

Because of its working environment, the choice of material for a gas filled thermal system is effectively limited to stainless steels, most probably the "18-8" austenitic type such as A.I.S.I. 321 which is readily obtainable commercially. Any fill gas used must be totally inert to this steel at the phial operating temperature, which could be as high as 850 ^{o}C (see chapter 8 for a discussion of phial operating temperatures), as any tendency to react with the thermal system walls would cause a gradual pressure drop. Stainless steels have the benefit of a protective oxide layer, but in a phial undergoing a thermal cycling regime this layer cannot be relied upon to separate a reactive gas from the steel.

Of course the cheapest fill gas would be air, but even under conditions of parabolic oxidation the oxygen content would be gradually taken up as the oxide layer on the stainless steel thickened. For example Mortimer and Sharp (44) measured a weight gain of 0.15 mg/cm^2 on a 20% Cr ferritic steel after exposure to 1 atmosphere of oxygen at 750 ^{o}C for a period of 40 hours. This is equivalent to an oxygen uptake of approximately 0.1 cc at S.T.P. per cm^2 of surface area and if a typical phial is assumed to have a volume of 0.5 cc and an internal surface area of 4 cm^2 (see chapter 8), then it will be appreciated that the oxygen partial pressure would be rapidly reduced.

An inert gas must therefore be chosen as a filling for F.F.D. thermal systems. Nitrogen and carbon dioxide are examples of cheap and what would normally be considered fairly inert gases. However at the high temperatures encountered in a phial, both of these would react with stainless steel. Smith and Evans (45) have found that 1 atmosphere of nitrogen would react with a 20% Cr - 25% Ni - 1.5% Ti stainless steel when heated at temperatures up to 1140 ^{o}C, forming precipitates of CrN, Cr_2N, and TiN. Carbon dioxide is well known to react with stainless steels (46), being reduced to carbon monoxide leaving an oxide layer on the metal surface. In some instances this reaction can proceed further, the carbon dioxide being reduced to carbon which is then taken up by the metal.

Because of the danger of these reactions it is essential that the thermal systems be filled with a noble gas, such as helium or argon. With such a fill gas the danger of reaction with the phial walls would be completely ruled out.

6.3 Permeation

Permeation is the passage of a gas through the metal itself and generally the rate of permeation increases exponentially with temperature. So with the phial of a gas filled F.F.D. running at up to 850 ^{o}C, there could possibly be a gradual loss of gas. This may well have been happening in the case of gas thermometers where, to quote The Instrument Manual (47), "It is found at the higher temperatures that certain metals become porous to gases, thereby lowering the pressure in the system. Some manufacturers, therefore, specify a maximum temperature of 800 ^{o}F (427 ^{o}C) for their products". A gas thermometer is similar to the device under discussion here, consisting of a phial, capilllary and a bourdon tube which operates a gauge giving a temperature reading. The thermometer is pressure filled with a gas, which is most usually nitrogen (47, 48).

The pressure dependence of the permeation of diatomic gases through metals has been generally found to comply with Henry's law (49, 50):-

$$\text{Permeation rate} = kP^{1/2} \qquad \ldots\ldots\ (6.1)$$

where k is a constant and P is the pressure driving the permeant through the membrane. This finding indicates (from the law of mass action) that the gas does not pass through the membrane as molecules, but that the gas molecules dissociate into atoms which then permeate the metal. Permeation is a far more complex process than diffusion through holes, and Shupe (51) has indicated 5 stages through which the gas must go to permeate a metal barrier.

1) Adsorption of molecules as atoms at the upstream surface.
2) Transition of the atoms from the adsorbed state to the sublayer immediately inside the upstream surface.
3) Diffusion of the atoms through the volume interior.
4) Transition of the absorbed atoms from the sublayer immediately inside the downstream surface to an adsorbed state on this surface.
5) Desorbtion from the downstream surface.

Any one of these steps, or a combination of several of them can be the rate limiting factor in permeation.

In stage 3 (above), the gas in solution in the metal diffuses through the metal wall, and the rate of diffusion will be given by Fick's law:-

$$J = -D \frac{\partial c}{\partial x} \qquad \ldots\ldots\ (6.2)$$

where D is the diffusion constant and $\frac{\partial c}{\partial x}$ is the concentration gradient. Clearly for mass transfer to be rapid, both D and $\frac{\partial c}{\partial x}$ must be large. In the steady state situation the maximum possible concentration gradient will be given by:-

$$\frac{\partial c}{\partial x} = \frac{s}{t} \qquad \ldots\ldots. \ (6.3)$$

where s is the solubility of the gas in the metal and where t is the thickness of the metal wall.

Clearly then, in order to be able to permeate a metal membrane, a gas must be soluble in the bulk metal. However having a high solubility does not necessarily mean that a gas will permeate a metal membrane, as any one of the stages 1, 2, 4 and 5 mentioned above could limit the permeation rate.

Fortunately one group of gases are known not to permeate any metal at all, to quote Norton (49), "There seems to be one generalization: No rare gas permeates any metal. This has been tested over a large temperature range, and there has been no reliable report of the neutral rare gas showing any permeation through a metal wall". There are two reasons for this, the first being that the inert gases have been found to have undetectably low solubilities in metals (52). This is because the total free energy change when an inert gas dissolves in a metal is very positive, due to the positive lattice strain energy not being compensated for by any negative chemical binding energy. Therefore it is energetically very unfavourable for a noble gas to dissolve in a metal. The second reason concerns the first stage of permeation, the adsorption of the gas onto the metal surface. To be adsorbed, a gas must first undergo physical adsorption (53) where it is bound to the surface by Van de Waals forces. The binding energy is normally less than 8 K cal/mole and in the case of inert gases can be very low (e.g. argon on tungsten ~1.9 K cal/mole). Inert gases can only undergo physical adsorption and as the temperature is raised the physically absorbed inert gas will tend to desorb as the probability of an atom having the necessary desorption energy increases. Reactive gases, however, can pass from a physically absorbed state to a chemisorbed state (53) characterized by a much higher binding energy, possibly up to 200 K cal/mole. Chemisorbed atoms will therefore remain on the surface at much higher temperatures, until they have sufficient activation energy to either desorb from the surface, or move into the bulk metal. Thus the chemisorbed state aids the transition of the gas from the atmosphere to solution in the metal, and the absence of this state is another barrier to the permeation of noble gases through metals.

Permeation rates of reactive gases through different metals have been measured by various researchers and a summary of results is shown in fig. 12. It will be noticed that in the examples shown in fig. 12, the permeation rate increased exponentially with temperature. This is not surprising since a permeating gas must surmount a series of energy barriers in going from a gaseous state to solution and vice versa and in diffusing through the bulk metal. The probability of an atom having sufficient energy to jump a barrier will increase exponentially with temperature and hence the permeation rate increases in a commensurate manner.

The choice of a noble gas to fill a F.F.D. thermal system would rule out the chance of any gas loss due to permeation. However permeation is a two way process and gas from the outside environment might permeate into the thermal system until the partial pressure of the permeant on the inside was the same as that on the outside. A phial in its working environment will encounter a range of gas mixtures, varying between:-

a) Air
   78% Nitrogen, 21% Oxygen (by volume)

b) Unburnt gas - air mixture
9.5% Methane, 18.9% Oxygen, 71.6% Nitrogen

c) Burnt gas - air mixture
9.5% Carbon Dioxide, 18.9% steam, 71.6% Nitrogen

From fig. 12 it will be observed that nitrogen has a high permeation rate through iron, and in the three gas mixture examples (above) nitrogen formed a large volume fraction of the mixture. Thus the possibility of nitrogen permeation must be considered, since for pure iron the fill pressure of a device originally filled with inert gas could rise by as much as 0.78 atmospheres (79 kPa), which would seriously affect the F.F.D.'s performance.

In practice, however, nitrogen permeation into stainless steel thermal systems does not seem to occur, or at least only occurs to a limited extent. Experimental helium filled "18-8" stainless steel thermal systems were run for several thousand hours at high temperatures in a gas flame (see section 7-14) and in no case was any measurable increase in fill pressure observed. Mercury devices should also suffer from permeation, as the manufacturing process leaves very little residual air inside the stainless steel (A.I.S.I. 430) thermal system. Thus when at operating temperature the partial pressure of nitrogen in the phial would be very low and if nitrogen permeation took place, the partial pressure of nitrogen would gradually be raised to 0.78 of an atmosphere (79 kPa). Fig. 13 illustrates the effect of this magnitude of permeation on a Harper Wyman 5920 mercury F.F.D.. Line AC is a typical pressure - extension line for the capsule and line DE represents the point at which the valve is calibrated to open. The case considered is where 0.78 atmospheres permeated at a running temperature of 700 ^{o}C. The curve represents the way in which the pressure of the permeated gas would vary with capsule extension when the whole thermal system is at 27 ^{o}C. It will be seen that at the point B where the curve intersects the line AC, the valve is just open, thus if permeation occurred to this extent all valves would eventually be left permanently open. This has not been known to happen and it can therefore be assumed that permeation does not occur to any great extent, so clearly nitrogen permeation through stainless steel is much more limited than permeation through pure iron.

At first sight this is very surprising, as nitrogen is more soluble in stainless steel than in pure iron. For example at 900 ^{o}C, .0033 mass % of nitrogen can dissolve in pure α iron (52), whereas in A.I.S.I. 304 (18% Cr - 8% Ni-Fe) stainless steel at 900 ^{o}C, up to 0.25 mass % of nitrogen can be dissolved before nitride precipitation occurs. For A.I.S.I. 430 steel (18% Cr-Fe), the solution limit at 900 ^{o}C is a little lower than in 304, being 0.05 mass % (35), but this is still more than for pure iron. At 700 ^{o}C the situation is much the same, pure α iron dissolving .0015 mass % of nitrogen (52) and A.I.S.I. 304 stainless steel dissolving approximately 0.1 mass % nitrogen (35). The reason for this solubility difference is that iron (below 906 ^{o}C) has a BCC structure, whereas A.I.S.I. 304 stainless steel has a FCC structure and therefore much larger interstitial gaps. Therefore diffusion through the bulk steel cannot be the rate limiting process, and one of the other stages in the permeation process must be the cause.

Eschbach et al (55) in studying hydrogen permeation through stainless steel noted that "an oxide layer on the membrane reduced the permeability markedly", and a partial pressure of oxygen of a few torr in the hydrogen was found to reduce the permeability by a factor of 10.

Simplistically a protective oxide on a stainless steel will reduce the permeation since it forms a barrier between the metal and atmosphere, and in the case of a stainless steel phial running in a gas flame at red heat the oxide layer would be far thicker than that in Eschbach's work, and a far greater reduction in permeation would be expected in the F.F.D. phials.

Most metal oxides grow by the diffusion of metal ions (cations) through defects in the oxide, to the surface where they combine with oxygen from the air. This happens because the majority of the defects in the oxide lattice are cation defects, providing plenty of vacant sites to aid diffusion of the cations. Stainless steel has such an oxide and Hagel et al (56, 57) have measured the diffusion constant (D) of the cation in Cr_2O_3 at 1100 ^{o}C to be approximately 10^{-11} cm^2/sec, whereas they found that the diffusion constant for the anion was very much less, at 10^{-15} cm^2/sec. Because oxidation is mainly a process of metal diffusing up through the oxide to meet the oxygen, then atmospheric nitrogen will not be able to come into contact with the bulk metal, unless it can penetrate the oxide layer in some way.

There are three possible mechanisms by which nitrogen from the air could penetrate an oxide layer to reach the metal surface. These are:-

1) Gaseous diffusion through cracks in the oxide layer.
2) Diffusion of nitrogen via interstitial sites in the oxide lattice.
3) Substitution of nitrogen ions for oxygen ions in the oxygen sublattice and diffusion via a vacancy or exchange mechanism.

If the stainless steel is at a temperature where the oxide layer is fulfilling its protective role, any cracks should heal over quickly due to the formation of new oxide, thus the amount of nitrogen finding its way to the metal surface via mechanism (1) should be small. The probability of nitrogen dissolving interstitially in the oxide is low due to the large size of the ion (N^{3-} 0.92Å, O^{2-} 1.32Å, Cr^{3+} 0.63Å), therefore very little nitrogen is likely to find its way to the metal by means of mechanism 2. This leaves the possibility of the replacement of oxygen ions by nitrogen ions, which then diffuse through the oxide layer to the metal. This is unlikely to happen to any great extent for two reasons. First nitrogen ion substitution for oxygen ions is unlikely unless the partial pressure ratio PN_2/PO_2 becomes very high, due to the much higher heat of formation of Cr_2O_3 (-270 K cal/mole) than CrN (-29.4 K cal/mole). Thus the amount of nitride to be found in a normal oxide layer is likely to be very small. Secondly, it has been pointed out earlier that the diffusion constant for oxygen anions is very low in Cr_2O_3. If nitrogen ions in a layer of oxide on a stainless steel were assumed to behave in a similar manner, then the diffusion constant for them would be in the order of 10^{-15} cm^2/sec at 1100 °C and 10^{-19} cm^2/sec at 800 °C. Table 6 summarizes diffusion constants for ions in various media, and it will be noted that if the assumptions made above are reasonable, then nitrogen diffusion in a stainless steel oxide at 800 °C could be up to 10^{12} times slower than nitrogen diffusion in iron. These, then, are indications that an oxide layer does indeed act as a very effective barrier to nitrogen permeation.

Examination of table 6 suggests that oxygen permeation would be fast, since D for oxygen in iron is close to that of nitrogen at 800 °C, and an oxide layer would give a high concentration of oxygen ions at the metal surface. This is not the case because oxygen solubilities in metals other than those in group IV A and V A of the periodic table tend to be very low indeed (58). Taking pure α iron as an example, the solubility of N_2 at 800 $^{\circ}C$ has been measured at 2.3×10^{-3} mass % (52), whereas the solubility of oxygen may be as low as 1.5×10^{-7} mass % at 750 $^{\circ}C$ (58).

6.4 Choice of fill Gas

Section 6.2 and 6.3 pointed out that only noble gases could be used to fill F.F.D. thermal systems, as these are the only gases which will not chemically combine with the hot phial walls and which will not permeate out of the thermal system. In section 6.1 it was suggested that helium would be a good choice of fill gas as it would enable leaks to be detected and also its high thermal conductivity (some six times that of air) might be an advantage. If helium were to prove too costly, then argon could be used as a substitute.

It is suggested that a well made thermal system filled with either of these gases would be able to sense a gas flame for a long period of time, without any change in the amount of gas it contained.

CHAPTER 7

EXPERIMENTAL WORK

7.1 Gas flow versus Pressure drop Measurements

The multi-purpose test rig shown in figures 14 and 15 was used to determine the gas flow rate through a valve at different values of pressure drop and valve lift. Nitrogen gas at a pressure of 1,000 kPa was fed to a "Govenaire 1062" pressure regulator (R1), which enabled the output pressure to be accurately regulated over the range 15 to 1,000 kPa, the pressure being monitored by a gauge, G1. A needle valve V9, allowed gas to flow at a controlled rate to two "rotameter" flowmeters F1 and F2. F1 covered a nitrogen flow range of .04 to .3 cubic metres per hour and F2 measured over the range 0.2 to 1.8 cubic metres per hour. Both flowmeters were calibrated to an accuracy of $\pm$2% indicated flow + 0.2% of the full scale reading. The valves V6 and V7 enabled the correct meter to be selected to suit the gas flow rate. From the flowmeters, the gas passed via a 12 mm diameter pipe to the inlet of the F.F.D. being flow tested. A pressure tapping was taken 80 mm upstream from the union to which the experimental valves were screwed and the pressure at this tapping was measured by a gauge G2, scaled to read 0 to 5 mb to an accuracy of $\pm$ .05 mb. A "bubbler" relief valve was provided to protect this gauge.

An experimental inconel X 750 capsule, similar to that described in section 7.2 was brazed to a capillary tube and a threaded stud was bonded to its top surface. The pressure extension characteristics were measured by the method outlined in section 7.2. The capillary and capsule were bonded into a F.F.D. valve body (as in figure 32) and a valve plate was screwed down the stud until the capsule was pulled lightly into tension. The valve plate was locked in this position by the application of cyanoacrilate adhesive to the screw thread. The resulting valve was similar to that shown in figure 32, except that the phial end was open allowing the capsule to be pressurized. The inlet of this valve was screwed to the flow test union on the test rig and the open end of the phial was connected to the roving connector (see fig. 14).

The turbulent flow pressure drop (Δp) through such a valve at gas velocities of less than mach 0.2 can be expressed as:-

$$\Delta p = \rho F^2 \; (C_v + C \; (D,h) \;) \qquad .... \; (7.1)$$

where ρ is the gas density and F is the flow rate at S.T.P.. The bracketed term is the flow resistance of the valve which can be split into two component parts, C_v, the resistance due to the valve body and C (D,h), the flow resistance across the valve seat which is a function of its diameter (D) and the valve lift (h).

First the pressure drop due to the valve body was measured in the following manner. The pressure regulator (R1) was adjusted to give sufficient pressure to the capsule, so that the valve plate just lifted off its seat. This was indicated by the start of gas flow through the valve. The capsule pressure was noted and the pressure was then increased to give a valve lift of 0.75 mm (determined from the previously measured pressure-extension curve). The flow of gas through the valve was varied using V9 and the pressure drops measured using G2. These nitrogen flow rates were converted to natural gas flow rates by multiplying by 1.285 (the ratio $\rho N_2/\rho$Nat gas. See equation 7.1). These high valve lift pressure drops indicated the resistance due to the valve body and are reproduced in fig. 16.

The capsule pressure was adjusted to give valve lifts varying from 0 to 0.25 mm, the nitrogen flow rate varied and the corresponding pressure drop-flow relationship was measured for the different valve lifts. The pressure drop due to the valve body at each particular flow (fig. 16) was then subtracted from the measured pressure drop at that flow, to give the pressure drop due to the valve seat itself. This pressure drop-flow-valve lift relationship was plotted and the gas flow required to give a valve seat pressure drop of 0.5, 0.75 and 1.0 mb at the different values of lift were found by interpolation. These results are shown in fig. 17. Fig. 18 illustrates the leading dimensions of the valve seat and valve plate used in this experiment.

7.2 Measurement of Capsule Pressure Extension Curves

The capsule was brazed to a capillary tube and the top boss was ball sealed. The capillary was connected to the roving connector on the multi-purpose test rig and the capsule clamped into the capsule extension measuring apparatus illustrated in fig. 19. The dial indicator enabled capsule extensions to be measured to .0025 mm.

To measure the pressure-extension curve, the capsule internal pressure was adjusted by means of the pressure regulator R1 and the pressure measured on gauge G1, (fig. 14), which was calibrated to measure 0 to 689.5 kPa to an accuracy of $\pm$6.89 kPa. Several special capsules were made for this work by Pressure Sensors Ltd. of Axminster and Fig. 20 shows the (rising) pressure-extension curve for one of them (capsule number 7). These capsules were made from .075 mm thick inconel X 750 and precipitation hardened. The active diameter was 18 mm and there were 2½ sinusoidal corrugations with an amplitude of 0.32 mm (peak to peak) and a wavelength of 2.1 mm. It will be observed from fig. 20

that this capsule came very close to having a linear pressure-extension performance and a possible linear approximation is suggested in fig. 20.

Figs. 21 and 22 illustrate the measured (rising) pressure-extension curves of two 18 mm diameter Harper Wyman mercury F.F.D. capsules (capsules 4 and 31 respectively). These had .127 mm thick diaphragms made from A.I.S.I. 302 stainless steel, the dimensions of which are illustrated in fig. 23 (see also the section through such a capsule shown in fig. 24). It will be observed that the pressure-extension curves for these capsules were less linear than those of the inconel X 750 type. During the course of this work many of these Harper Wyman capsules were tested and a considerable variation in their pressure-extension characteristics was noted. The pressures needed to produce an extension of 1 mm varied between 470 kPa and 660 kPa, fig. 21 showing a very flexible example and fig. 22 illustrating a more average capsule.

The inconel X 750 capsules were found to exhibit no measurable hysteresis, however a considerable hysteresis was measured for the Harper Wyman capsules. The curves shown in figs. 21 and 22 were measured using rising pressures and higher extension readings were noted if the measurements were made with reducing pressures. Fig. 25 shows a hysteresis curve measured for a Harper Wyman capsule. Curve BCA was the difference between decreasing pressure readings and rising pressure readings and loop C-D-B-C shows the amount of hysteresis measured when the capsule was cycled between its full extension (at 586 kPa) and an intermediate extension (at 152 kPa).

7.3 Experimental Thermal Systems - Production and Testing

Experimental phial and capillary assemblies were constructed as shown in fig. 26. The phials were machined from solid A.I.S.I. 304 stainless steel, two sizes being made, which gave an internal phial volume of either 300 mm^3 or 500 mm^3 when sealed. The phials were brazed to the capillary using 'Nicrobraz LM', a proprietary high temperature stainless steel brazing alloy. The other end of the capillary was brazed to a capsule, the pressure-extension performance of which was measured as described in section 7.2.

The experimental thermal systems were filled with helium and sealed by the method shown in fig. 27, the sequence of events being as follows:-

a) The thermal system was placed in a hydraulic press which was fitted with hardened steel jaws. The phial was clamped so that the distance L (see fig. 27) was the correct length to give the desired phial volume. (24 mm for 300 mm^3 phials, 27 mm for 500 mm^3 phials).
b) The capsule was clamped in the capsule extension measuring apparatus to enable the filling process to be monitored.
c) The filling pipe was fitted to the open end of the phial by means of a quick release coupling.
d) V2 was shut, V1 opened and the system evacuated to less than 10 kPa pressure.
e) V1 was then shut, V2 opened and the regulator R1 adjusted to give the correct fill pressure (measured by G2), or capsule extension (measured by the D.T.I.) depending upon which criterion was being used.
f) Steps (d) and (e) were repeated twice to ensure complete removal of air from the system.

g) The hydraulic press was then operated so as to crush the phial. The press was set to give a force of approximately 5,000 kg, which temporarily sealed the end of the phial.

h) V1 and V2 were shut and the fill pipe was removed. The dial gauge on the capsule extension measuring apparatus was checked to see if there was any gas leakage.

i) The open end of the phial was packed with DRY 'Nicrobraz LM' and heated to orange heat with an oxy-acetylene torch. It was necessary to repeat this step once more to obtain a good braze seal.

j) The hydraulic press pressure was released and the dial gauge checked to see if the braze seal had leaked.

This method was capable of producing well sealed thermal systems. Unfortunately the success rate was never very high, particularly when using the larger diameter 500 mm^3 phials, when approximately 30% of seals leaked on removal of the hydraulic pressure. However this technique was adequate for producing a sufficient number of samples for experimental purposes, especially as most of the thermal systems successfully filled showed no tendency to leak later, even when subjected to arduous tests. A photograph of a completed thermal system with a 500 mm^3 phial is reproduced in fig. 28.

To measure the performance of completed thermal systems, a thermocouple was spot welded to the centre of the phial, which was inserted into a tube furnace and a digital thermometer was connected to the thermocouple leads. The phial was heated and readings of phial temperature versus capsule extension were taken for phial temperatures up to 700 ^{o}C (going to higher temperatures than this risked melting the Nicrobraz seals).

Figs. 29, 30 and 31 show the measured values (crosses) of capsule extension versus phial temperature for thermal systems 7, 4 and 31 respectively (made using capsules 7, 4 and 31 - see section 7.2). After testing, thermal system 7 was sectioned and its dead volume measured to be 59 mm^3 (± 5 mm^3). The phial volume was estimated at 300 mm^3 (± 10 mm^3) and the fill pressure (Pf) was 260 kPa (± 10 kPa) absolute. This data, along with the linear approximation to the pressure extension curve ($\bar{X}$ = 2.28×10^{-9} m/Pa) shown in fig. 20, was used to produce the computed performance prediction illustrated in fig. 29.

Experience with thermal systems made using Harper Wyman 18 mm^3 diameter capsules has shown them to have a typical dead volume of 60 mm^3 (± 10 mm^3). The phial volumes of thermal systems 4 and 31 were both estimated to be 500 mm^3 (± 10 mm^3). The fill pressures for thermal systems 4 and 31 were 278 kPa (± 10 kPa) absolute and 266 kPa (± 10 kPa) absolute respectively. Computer predictions of performance were made using this data and the measured capsule pressure-extension performance and these are shown in figs. 30 and 31. The reason for the discrepancy between the conputed predictions and the measured performance is discussed in chapter 8.

7.4 Experimental Flame Failure Devices - Construction and Testing

The thermal system was first of all made and tested in the way described in section 7.3 and was bonded into a diecast F.F.D. body as shown in fig. 32. A threaded stud was bonded to the top of the ball seal using epoxy adhesive, the stud being held perpendicular to the valve seat by a jig whilst the adhesive was setting. The outlet of the F.F.D. was then screwed onto the flow test union of the multi-purpose test rig. The phial was instrumented with a thermocouple, placed in a tube furnace and heated until it was at the temperature at which the F.F.D. was intended to start opening. A standard 25 mm diameter valve plate (see fig. 18) was screwed onto the threaded stud until it came into light contact with the valve seat, so that the valve was just shut.

The water level in the 'bubbler relief valve' on the test rig was set so that the dip tube end was 2.5 cm below the surface and R1 and V9 (see fig. 14) were adjusted (with valves V7 and V8 open) so that bubbles escaped at a rate of approximately one per second from the dip tube. The valve plate was slowly unscrewed, until bubbles just stopped appearing at the end of the dip tube, when the valve plate was locked in this position by application of cyanoacrilate adhesive to the screw thread.

After constructing the F.F.D. in this way, it was leak checked. The phial was allowed to cool, valve V8 was closed and needle valve V9 adjusted to give a reading of 50 mb on the manometer. V9 was then closed and the water column in the manometer was observed for any gradual loss of pressure.

If the valve was leak free, the cover plate and rubber gasket were fitted to the back of the F.F.D., which was then taken off the flow test union. The inlet of the F.F.D. was screwed onto the flow test union and the instrumented phial was replaced in the tube furnace. The phial was heated until the F.F.D. opened and R1 and V9 were adjusted to maintain a gas flow through the valve which gave a pressure drop reading on G2 of 0.75 mb. Readings of phial temperature against the nitrogen flow rate at 0.75 mb pressure drop were recorded up to a phial temperature of 700 ^{o}C. Fig. 33 shows the flow-temperature curve for F.F.D. number 31 (constructed from thermal system number 31), with the nitrogen flow rates converted to natural gas flow rates. Fig. 34 shows a photograph of a completed gas filled F.F.D. with a 500 mm^3 phial.

7.5 The Cooling Rates of F.F.D. Phials

The cooling rates of a 300 mm^3 and a 500 mm^3 experimental phial (made in the way described in section 7.3) were measured at an ambient temperature of 22 ^oC. A thermocouple was spot welded to the centre of the phial which was supported 25 mm above a cooker type gas burner on the life test rig (see fig. 51), so that the thermocouple was in the centre of the flame, facing upwards. The burner was turned on and the F.F.D. phial was allowed to reach a stable running temperature. With the burner full on this was found to be 693 ^oC for the 300 mm^3 phial and 690 ^oC for the 500 mm^3 phial. The burner was turned off and readings of phial temperature against time were taken for a total of 4 minutes. Fig. 35 shows the cooling rate measurements for the 300 mm^3 and the 500 mm^3 phials.

A 30 mm long by 3 mm diameter mercury F.F.D. phial was also tested (results not shown in fig. 35). It was found to run at 795 ^oC with the burner full on and cooled to 443 ^oC in 10 seconds, 340 ^oC in 20 seconds and 280 ^oC in 30 seconds. This rate of cooling was very similar to that exhibited by the 500 mm^3 phial.

The cooling rate of a 300 mm^3 gas filled phial was also measured when it was placed above the burner in an oven at maximum temperature. The phial was instrumented with a thermocouple and supported 30 mm above the burner in a 'New World Conquest' gas oven. The phial was positioned so that the thermocouple was in the centre of the flame facing upwards. A thermocouple was also spot welded onto each of two 9 mm diameter by 140 mm long stainless steel rods. One of these rods was placed on the wire baking shelf at the centre of the oven and the other was placed at the centre of the oven floor, with the thermocouple uppermost. The leads from these three thermocouples were taken out through the oven door and insulated so that the oven door could be closed on them without causing a short circuit. The oven was set to gas mark 9 and left for one hour. After this time the thermocouple at the oven centre was reading 247 ^{o}C (gas mark 9 is 250 ^{o}C) and the thermocouple on the oven floor was reading 146.5 ^{o}C. The F.F.D. phial temperature was found to have stabilized at 660 ^{o}C. The oven was then turned off and readings of the phial temperature against time were taken for a period of 4 minutes. These are shown in fig. 35.

7.6 Capsule Volume/Extension Measurements

The capsule to be tested was brazed to a capillary tube, ball sealed and the pressure-extension performance was measured as detailed in section 7.2. The capsule was bonded into a valve body with ¼" B.S.P. connections (as in fig. 32), the inlet of which was plugged so that it was completely leak tight. The gasket and cover plate were then fitted to the back of the body, as shown in fig. 32. A hole was drilled in a ¼" B.S.P. plug and the end of a 600 mm long, 1.2 mm bore glass capillary tube was bonded into the plug using epoxy adhesive. The valve body was completely filled with room temperature water, great care being taken to remove all air bubbles from inside the body. The ¼" B.S.P. plug with the glass capillary tube was screwed into the outlet of the valve body and the assembly was laid down so that the capillary tube was exactly horizontal. The position of the meniscus in the capillary tube was marked.

The capillary tube connected to the capsule was coupled to the test rig's roving connector and the capsule internal pressure was adjusted using pressure regulator R1 (fig. 14). Readings of the water column length in the glass capillary tube were taken at different capsule pressures. The water column lengths were converted to volumes, the pressure readings converted to capsule extensions (from the pressure-extension data) and the resulting volume-extension relationship plotted.

Fig. 36 shows the volume-extension relationship for a typical Harper Wyman 18 mm diameter capsule. It will be observed that there was a linear relationship between extension and volume as suggested by equation 5.3 (see section 5.3). This gradient corresponded to a value of S of 0.48. The same measurements were made for an inconel X 750 capsule, of the type used to make thermal system number 7, and again a linear relationship was observed, which for this capsule corresponded to an S value of 0.49.

The effects of force on the capsule extension-volume relationship were also investigated. To do this, the capsule pressure-extension performance was measured with the capsule subjected to various central loads on the top diaphragm. This was done by mounting the capsule extension measuring apparatus vertically (fig. 19b), adding weights to the top of the D.T.I. and then measuring the pressure-extension relationship. The capsule, capillary and valve body were assembled as before, but this time a spring was arranged to restrain the capsule with a load corresponding to one of those used when measuring the loaded pressure-extension data. A low rate spring was chosen to minimise the increase in spring force as the capsule extension increased. The valve body was filled with water and the volume-extension relationship measured.

Fig. 36 shows the result of a 10N load on the volume-extension relationship of a Harper Wyman 18 mm diameter capsule, It will be observed that the force had little effect on the gradient, but affected the intercept with volume axis. With no load a 2.5 mm^3 intercept was observed, whereas with a 10N load a 13.5 mm^3 intercept was obtained.

7.7 Variation of Pressure Sensitivity with Capsule Thickness

Difficulty was experienced in obtaining Harper Wyman 18 mm diameter capsules in anything other than the standard 0.127 mm diaphragm thickness. Because of this the variation of pressure sensitivity with diaphragm thickness was measured by thinning down standard capsules using an electropolishing technique.

The capsule to be thinned was prepared by brazing it to a capillary tube and ball sealing the top boss assembly. The capsule and capillary were fitted into the electropolishing electrode assembly in the way shown in fig. 37. An electropolishing bath was made up using 95% glacial acetic acid and 5% perchloric acid and the electrode assembly and capsule were submerged beneath this mixture. Two 3 amp power supplies were connected to the electrodes in the manner shown in fig. 37.

The temperature of the electropolishing bath was monitored throughout the electropolishing process and maintained between 14 and 20 ^{o}C by adding dry ice to the bath when required. Experience with the electrode assembly (fig. 37) showed that the current to the front electrode had to be set at 1.6 A and that to the rear electrode set at 2.6 A, otherwise a pitted surface finish was produced on the capsule, instead of the desired highly polished finish. The power supplies were set to give these currents, then were switched on simultaneously and switched off 20 seconds later, to avoid overheating the bath. This was repeated as many times as was necessary to remove the correct amount of metal from the diaphragms (one 20 second burst very approximately removed 0.002 mm of metal), the bath being allowed to cool back to 14 ^{o}C between electropolishing cycles.

Several samples were prepared, each thinned to a different extent up to a maximum of 20 electropolishing cycles. The pressure-extension curves were then measured, after which the capsules were set in "metset" resin and sectioned down their centre lines. The section was carefully polished and the thickness of the top and bottom diaphragms was measured at each of the 7 positions shown in fig. 23 using a microscope with a calibrated filar eyepiece. The mean of all 14 thickness measurements and the standard deviation were calculated. The mean pressure sensitivity of the capsules ($\bar{X}$) was obtained from the pressure extension data by the calculation:-

$$\bar{X} = \frac{.889 \times 10^{-3}}{\Delta P} \qquad \ldots\ldots\ (7.2)$$

where ΔP was the pressure change needed to extend the capsule from .127 mm to 1.016 mm extension. This calculation was used to avoid any complication caused by variations in capsule starting pressures.

The variation of $\bar{X}$ with mean thickness for Harper Wyman 18 mm diameter, A.I.S.I. 302 capsules (see figs. 23 and 24) is shown in fig. 38. The error bars in the mean thickness direction were the standard deviations in the thickness measurements for each particular capsule. Measurements 4b and 5b were made using unthinned capsules. Later a few ready made thin capsules, produced using the standard press tools, became available. Point A on fig. 38 is that measured for a capsule with .107 mm thick diaphragms and point B that measured for a capsule with .0762 mm thick diaphragms. These thicknesses were the nominal thickness of the sheet metal used to make the diaphragms.

7.8 Capsule Pressure-Load Performance

A 18 mm diameter Harper Wyman capsule was prepared by bonding a 6BA threaded stud onto its top boss and brazing a capillary tube onto the lower boss. The 6BA stud was screwed into the D.T.I. on the capsule extension measuring apparatus (as shown in fig. 19c) and locked firmly into position. The capsule lower boss was gripped very firmly by the jaws on the capsule extension measuring apparatus. Thus the capsule was firmly fixed into position, and positive and negative loads could be applied to the top boss through the D.T.I.

Positive loading was investigated by mounting the capsule extension measuring equipment vertically as shown in fig. 19b. The capsule was pressurized to give a certain extension, then loads of up to 20N were applied to the top of the D.T.I. and the pressure required to restore the capsule to its original extension was recorded. This was repeated for different values of capsule extension, up to a maximum of 1.0 mm.

The extension measuring equipment was then inverted as shown in fig. 19c and a load of 20N was added to the weight pan. The capsule pressure was increased to give a 1.0 mm extension, then the load was gradually reduced and the pressure required to restore the capsule extension to 1.0 mm recorded. This was repeated for different values of capsule extension.

Fig. 39 shows the result of these measurements and it will be noted that the pressure-load measurements all lay in very straight, parallel lines. This indicated a very stable capsule pressure effective area throughout the entire load and pressure range. The pressure effective area measured along line A-B on fig. 39, was found to be 0.992 x 10^{-4} sq. metres and the ratio of pressure effective area to active area was 0.324.

7.9 Permanent Set of Capsules

An unused Harper Wyman A.I.S.I. 302 steel, 18 mm diameter capsule was prepared by ball sealing the top boss and brazing a capillary onto the bottom boss. The capsule was clamped in the capsule extension measuring apparatus (see fig. 19a), the D.T.I. zeroed and the capsule pressurized to an extension of 0.4 mm. It was left at this extension for approximately one minute, then the pressure was reduced to zero and the residual extension (called permanent set) showing on the D.T.I. recorded after an interval of one minute. The pressure was then increased to 138 kPa and the extension recorded again.

The capsule was then taken to progressively higher extensions and the zero pressure and 138 kPa extensions recorded after each extension of the capsule. Because these capsules were made with the diaphragms sprung together slightly, permanent set was masked until it became sufficiently large to exceed this prestress. It was for this reason that 138 kPa extensions were measured to check for hidden permanent set. Fig. 40 shows the permanent set measurements and the change in 138 kPa extension plotted against maximum extension for several Harper Wyman A.I.S.I. 302 capsules.

Capsule number 7 (see fig. 40) was set in "metset" resin and then sectioned down its centre line. Microhardness readings were taken at different positions on the diaphragms and were found to vary between H_V 340 and 383.

Several Harper Wyman 18 mm diameter capsules were made with 0.127 mm thick 17-7 PH diaphragms. The diaphragms were formed using annealed material and the finished capsule assembly was later heat treated by maintaining it at 760 ^{o}C for 90 minutes, followed by 30 minutes at room temperature then 90 minutes at 565 ^{o}C. This process precipitation hardened the diaphragms and the capsule was tested as described above.

The heat treatment removed all capsule prestress, so permanent set was not masked and the permanent set and 138 kPa extension readings increased in unison as the capsules were taken to higher maximum extensions. It was found that extension to 1 mm gave a permanent set of between 0 and .06 mm for the samples tested. The hysteresis of the capsules was checked over the extension range 0 to 1 mm and found to be less than .005 mm (much less than the standard capsule - see fig. 25).

7.10 Fatigue Life of Capsules

Part of the multi-purpose test rig was dedicated to the pressure cycling of capsules. Referring to fig. 14, nitrogen gas from a cylinder was regulated down to a set pressure by pressure regulator R1. The nitrogen flowed through shut off valve V2 to a 3 way A.C. solenoid valve V10, which was operated by an electronic control unit. V10 opened to allow the gas to flow to 4 capsules, connected to the test points (see fig. 14). The capsules were then pressurized to the level set by R1. After a period of time set by the control unit, V10 changed over and allowed the gas pressurizing the capsules to be exhausted to the atmosphere via V5, which was left open. V3 was normally left shut. Thus as V10 alternated between its two positions, the capsules were cycled between atmospheric pressure and a high pressure set by R1. If desired V5 could be left shut and the capsules cycled between the pressure set by R1 and a lower pressure set by back-pressure regualtor R2. A pressure switch was arranged to stop the rig from operating when the nitrogen cylinder ran out of gas.

Fig. 41 shows the control circuit which operated V10. Waveform generator IC1 produced a square wave output which could be varied between 0.6 Hz and 3 Hz by RV1. The output of IC1 was buffered by IC2 which drove TR1. This transistor switched the current passing through the coil of RL1 on and off, and the contacts of RL1 controlled the 240 V A.C. supply to solenoid valve V10. A resettable counter was provided to count the number of cycles.

The 4 capsules to be tested were ball sealed and brazed to a capillary tube. The pressure-extension curves were measured and as these varied considerably, a compromise setting for the cycling pressure was decided upon, so that each of the 4 capsules would be cycled to an extension somewhere in the desired range. The capsules were bonded into a valve body (as in fig. 32) using "metset" F.T. resin, so that they could be easily broken from the valve body enabling it to be reused many times. The inlet on the body was sealed and the rubber gasket and cover plate were fitted to the back of the body. A pressure switch set to operate at 20 kPa was screwed into the valve body outlet.

The capillary tubes were connected to the test points and the pressure switches plugged into the leak detector unit (fig. 42). The cycling controller was switched on and the capsules were cycled between atmospheric pressure and the set pressure, until one had developed a leak sufficient to operate the pressure switch. This switched current to the gate of one of the C103YY thyristors in the leak detector unit, turning it on. When turned on the thyristor pulled the base of TR1 in the control unit (fig. 41) to below the OV level, turning off the transistor and preventing the rig from cycling any more. A L.E.D. on the leak detector unit was illuminated to show which capsule had leaked. Even if the pressure switch opened its contacts again, the rig would not resume cycling, as the C103YY thyristor would remain conducting until the control unit was switched off and then on again. In this way, the rig cycled the capsules until approximately 3 atmosphere cm^3 of gas had escaped from any one of them.

In all 61 capsules were tested in this way, up to a maximum of 100,000 cycles. Fig. 43 shows the number of cycles at failure, plotted against the extension to which the capsule was cycled, for the 20 capsules which failed. It will be noted that no failures occurred at below 15,000 cycles and that most failures were due to cracking of the weld securing the top boss to the top diaphragm. Fig. 44 shows a section through such a cracked weld.

The cycling rig was also used to investigate the change in the pressure-extension curve with cycle life. Four standard Harper Wyman 18 mm diameter capsules were connected to the cycling test points and given 50 689 kPa cycles to "season" the capsules. The pressure-extension curves were measured and the capsules were then given 20,000 cycles between 0 and 620 kPa (this gave extensions between 1.062 mm and 1.030 mm). The pressure-extension curves were remeasured and the capsules were given another 80,000 cycles, after which the pressure-extension curves were measured again.

It was found that on the whole there was a very small increase in the extension at each point in the pressure-extension curve, which became greater as the number of cycles increased. The maximum increase observed in any reading at 20,000 cycles was .008 mm ($\pm$ .005 mm) and the maximum observed at 100,000 cycles was .015 mm ($\pm$ .005 mm).

7.11 Compliance of the Rubber Valve Seal

A valve plate (see fig. 18) was fitted onto the capsule deflection measuring rig in the manner shown in fig. 45. The valve plate was subjected to various central loads up to 25N and the deflections measured. The results of the experiment are shown in fig. 46. After the test it was found that a compression set of 0.014 mm remained. The stiffness of the test rig was also checked with the valve plate removed and it was found that a 20N load cased a deflection of 0.01 mm.

7.12 Creep of Rubber Valve Seal

This was measured for the standard valve plate (fig. 18) at different temperatures using the equipment shown in fig. 47. The rig consisted of an accurate D.T.I. (measuring to 0.0025 mm), which could be loaded and used to measure the deflection of the valve plate under that load. The valve plates were placed on the aluminium 'hot block' (see fig. 47) beneath the D.T.I.. This 'hot block' had a 14 W 10R resistor inserted through its centre and a GM473 thermistor positioned inside a boring just beneath the top surface. The circuit shown in fig. 48 monitored the upper surface temperature using the thermistor and varied the current through the 10R resistor to maintain a set temperature. An accurate mercury in glass thermometer was also inserted down a hole in the 'hot block' to enable its temperature to be read. This equipment was found to be capable of maintaining 'hot block' temperatures of up to 100 ^{o}C to an accuracy of $\pm\frac{1}{2}$ ^{o}C.

To set up the equipment, the temperature controller (fig. 48) was first of all adjusted to give the required 'hot block' temperature (for room temperature readings the controller was completely turned off). An unused valve plate was placed sealing lip downwards, at the centre of the 'hot block' and the UNLOADED D.T.I. positioned to measure the deflection of the centre of the valve plate. Mineral wool insulation was then placed over the top of the 'hot block' and valve plate to prevent heat loss and the rig was then left for one hour to allow the temperature to stabilize. The D.T.I. was zeroed and loaded to 10N as quickly as possible. One minute after loading the D.T.I. deflection reading was noted and after that deflection readings were taken at various times for a period of up to 1,000 hours.

Fig. 49 shows a plot of valve plate deflection against log. time in hours for different valve plates at various temperatures. It will be noted that after a settling period of approximately one hour, the creep rate stabilized to give a linear plot. The creep rates obtained varied between 0.0085 mm per log. decade and 0.0055 mm per log. decade.

7.13 Thermal Expansion of Rubber Valve Seals

This was measured using the creep measuring apparatus described in section 7.12. First the rate of expansion of this test rig with increasing 'hot block' temperature was measured. This was done by positioning the unloaded D.T.I. (see fig. 47) so that it measured the expansion of the centre of the 'hot block' and the top of the block was insulated with a wad of mineral wool to prevent heat loss. With the 'hot block' at room temperature, the D.T.I. was zeroed and the temperature controller was switched on to allow the 'hot block' to warm up to a given temperature. The apparatus was left for one hour for the temperature to stabilize, after which the 'hot block' temperature and D.T.I. readings were noted down. This was repeated for several temperatures up to 100 ^{o}C. Very consistent readings, corresponding to a rig expansion of 0.000946 mm per degree C were obtained (results plotted on fig. 50).

The rig was allowed to cool back to room temperature and a valve plate was fitted, sealing lip downwards, between the unloaded D.T.I. and the 'hot block'. The D.T.I. was positioned to measure the movement of the centre of the valve plate and the top of the valve plate and 'hot block' were insulated with a wad of mineral wool. The D.T.I. was zeroed and the temperature controller was switched on to allow the 'hot block' to warm up to a certain temperature. After being left to stabilize for one hour, the 'hot block' temperature and the D.T.I. reading were noted. This was repeated at various temperatures up to 100 ^{o}C.

Three valve plates were tested in this way and the results are shown in fig. 50. The thickness of rubber seal (the dimension A in fig. 18) was measured on each of the three valve plates and the mean value was found to be 1.4 mm for sample 1, 1.37 mm for sample 2 and 1.12 mm for sample 3. From the readings plotted in fig. 50 it will be seen that the expansion of the valve seal and rig was 0.001480 mm per degree C. Subtracting the value of the rig expansion from this gives an expansion due to the rubber seal alone of 0.00053 mm per degree C. This corresponded to a linear expansion coefficient for the silicone rubber used to make the valve seal (General Electric Silicone Products type HH250P) of approximately 3.8×10^{-4} per degree C.

7.14 Long Term Testing of Thermal Systems

To enable the reliability of thermal systems to be checked under likely operating conditions, the test rig illustrated in fig. 51 was constructed. The rig had two standard oven burners, one of which had a gas flame that burned continuously and the other was arranged to have a flame that cycled on and off. For safety, the continuously burning flame was sensed by a mercury F.F.D., which cut the gas flow back to a bypass rate if the flame extinguished. The cycling burner had a pilot fitted next to it, this pilot flame being sensed by another mercury F.F.D. which interrupted the gas supply to the cycling burner if the pilot extinguished. A cyclic timer operated a solenoid valve which controlled the gas flow to the cycling burner. This timer enabled the flame on and flame off times to be varied independently between 5 and 200 seconds. When the solenoid valve reinstated the gas flow to the cycling burner, the pilot immediately relit the burner and no unburnt gas was released to the atmosphere.

Five thermal systems were made up (as described in 7.3) and checked by placing the capsule in the capsule extension measuring apparatus (fig. 19a) and zeroing the D.T.I.. The free end of the D.T.I. was then pushed in under hard finger pressure, so that the capsule's two diaphragms were forced back together. This gave a measure of the capsule extension at ambient temperature to an accuracy of $\pm$ .01 mm. The 5 thermal systems were mounted so that the centres of their phials were in the continuous burner flame on the test rig and the height of the phials above the top of the burner was adjusted to 25 mm. The running temperature of the phials was checked by means of a thermocouple welded to one of them and found to be approximately 700 $^{\circ}$C. The phials were left in the flame and the capsule extension (with the phial cool!) was checked every few weeks. At the end of this life test, the results were as follows:-

Sample	Number of hours without failure	Duration of test-hours
1	335	(3603)
4	No failure	3603
6	No failure	4699
30	No failure	3239
35	No failure	3239

Samples 4, 6, 30 and 35 showed no significant change in the capsule extension (and therefore fill pressure) throughout the test.

Sample 1 showed signs of leaking when checked at 722 hours, however testing was continued and the leak seemed to stop, probably due to blockage by scale. The thermal system was examined to establish the cause of the leak, but none could be found and it is assumed that it was probably due to a leak of the nicrobraz phial end seal.

The condition of all 5 A.I.S.I. 304 steel phials after the end of testing was very good, with only some light surface scaling. Fig. 52 shows the condition of the phial on sample 35 after 2,700 hours continuous running. The phial on sample 1 was sectioned after it had spent 3,603 hours in the flame and there was found to be no significant metal wastage. The unaffected phial wall thickness was maintained at 0.55 mm.

Four flame failure devices were made up and calibrated as described in section 7.4. They were tested by measuring the nitrogen flow rate through the valve at 0.75 mb pressure drop, with the phial heated to red heat by a bunsen burner. The 4 devices were then mounted on the long term test rig with the centre of the phials placed in the cycling burner flame, 25 mm above the burner top. The timer was set so that the burner was on for 2½ minutes and off for 2½ minutes. The temperature of the phials was checked using a thermocouple spot welded to one of them and was found to vary between 75 °C and 700 °C when continuously cycling. These F.F.D.'s were left on test and the flow performance of the valve with the phial at red heat was rechecked every few weeks. Any change in this performance indicated a failure of the thermal system. At the end of this long term test the opening temperature of each F.F.D. was rechecked to see if it had deviated from the original calibration. The results obtained for the four flame failure devices tested were:-

Sample	Cycles without failure	Cycles in test	Set opening temp.	Opening temp. after test
13	36,798	(48,894)	----	----
25	30,240	(42.336)	----	----
32	No failure	38,532	299°C	319°C
34	No failure	38,532	308°C	306°C

The change in opening temperature for samples 32 and 34 were insignificant as the opening temperatures were only accurate to ± 10 °C. All four valves were found to be leak tight when checked after completion of the test.

Valve 13 successfully completed 36,798 cycles without performance change, but when rechecked at the end of the test was found to have failed shut. When the phial was sectioned it was found that the bore was very badly eccentric giving an original wall thickness of only .15 mm at one point. When examined after 48,894 cycles the thinnest part of the wall had corroded through, leaving a large split through which gas had escaped. Metal wastage was found to be up to .15 mm on thinner parts of the phial. Sample 13 successfully completed 30,240 cycles, but when examined at 42,336 cycles it was found to have a reduced flow capacity indicating a partial leak. The phial was sectioned and overall metal wastage was found to be approximately 0.1 mm leaving a minimum metal wall thickness of 0.26 mm (the bore was slightly off centre). The capsule was found to be leak tight and again the brazed phial end seal was assumed to be the prime suspect for the cause of the leak.

One of the mercury F.F.D.'s on the rig was taken off after a total of 3388 hours in service. The phial was sectioned and fig. 10 shows the condition of the internal surface. The metallic deposits which can be seen on fig. 10 were estimated to be up to 0.1 mm thick in places.

CHAPTER 8

THE DESIGN AND PERFORMANCE OF GAS FILLED FLAME FAILURE DEVICES

8.1 The Accuracy of Computer Performance predictions

Fig. 20, showing the pressure-extension performance of inconel X 750 capsule number 7, illustrates that some designs of capsule can make a close approach to having a linear pressure-extension performance. For such capsules the performance predictions made using a linear approximation to the pressure-extension performance were very accurate, as shown in fig. 29. The small discrepancies between measured and computed performances shown in fig. 29 were due to slight differences between the $\bar{X} = 2.28 \times 10^{-9}$ m/Pa linear approximation and the real pressure-extension curve and the fact that the measured value of S (the capsule volume factor - see section 7.6) was 0.49, rather than the 0.5 assumed by the computer program.

However capsule 7 was designed for high performance rather than ease of manufacture and mass produced capsules, such as those made for the mercury F.F.D. are not nearly so ideal in their behaviour. Fig. 21 illustrates the performance of capsule number 4, a Harper Wyman 18 mm diameter capsule, and the much higher non-linearity will be noted. The approximation to linearity ($\bar{X} = 1.8 \times 10^{-9}$ m/Pa) suggested for this capsule in fig. 21 was used to produce the computed performance prediction A in fig. 30. This prediction greatly overestimated the real performance of the thermal system (the crosses on fig. 30), therefore linear approximations cannot be used for capsules with non-linear behaviour such as that exhibited by capsule 4.

The reason for this performance overestimation is clear. The higher initial flexibility of a non-linear capsule means that the pressure in the thermal system is lower than that in an "equivalent" system with a linear capsule at the same extension when the phials are at ambient temperature. Thus the amount of fill gas in the non-linear system is less than that in an equivalent linear system. When the phial is heated, this smaller amount of gas has to produce sufficient pressure to combat an ever increasing capsule stiffness, thereby making the stroke of this thermal system less than that of an equivalent linear system.

The actual pressure-extension measurements for capsule 4 (the crosses on fig. 21) were fed into the computer to produce the performance prediction for thermal system 4, which is shown as curve B in fig. 30. It will be observed that this prediction was much closer to the measured thermal system performance than that produced using the linear approximation, but there was still a slight performance overestimation. A computer performance prediction made for thermal system 31 (this system also used a Harper Wyman 18 mm capsule), using the pressure-extension data shown in fig. 22, is illustrated in fig. 31. Again the computed performance prediction slightly over-estimated the real performance.

The reason for this discrepancy can be found in the high hysteresis of the Harper Wyman capsules. Fig. 25 shows hysteresis measurements made for such a capsule and explains the origin of the performance reduction. For example, if this capsule were made into a thermal system with a fill pressure of 152 kPa gauge (a fairly typical fill pressure) and the phial was heated taking the capsule to point B on fig. 25, then as the phial subsequently cooled back to ambient temperature, the capsule would follow the hysteresis curve to point C. At point C the capsule extension would be some 0.025 mm greater than it was when the thermal system was first filled (this is a slight simplification as it ignores the resulting small pressure reduction inside the thermal system). From then on, as the phial is heated and cooled, the capsule would follow the hysteresis loop C-D-B-C and approximately 0.025 mm of stroke would be permanently lost.

Therefore it can be seen that the computer predictions are very accurate indeed, the only source of error being a fairly small one due to capsule hysteresis. If need be the hysteresis could be allowed for, providing some idea of the expected thermal system performance was known. The capsule hysteresis could then be measured over the expected working range and the pressure-extension data used to produce the computer prediction adjusted accordingly. If computer predictions are made using a linear approximation to the true capsule pressure-extension curve, then optimistic performance predictions must be expected, unless the capsule used had a very linear performance.

8.2 The Computed Design Curves

To help a designer select the optimum thermal system design, computer predictions were made to show how the performance would vary with different design parameters. In this case, the capsule performance was assumed to be linear, as the introduction of non-linearity would tend to confuse the issues. Therefore these computed predictions represent the maximum achievable performance, which the designer should aim for, remembering that any non-linearity would reduce the performance.

For these design curves a realistic range of variation was estimated for each design parameter.

a) Phial Volume V_p

Size limitations restrict the variation of V_p to the range 0 to 1,000 mm^3, although it would be advatageous to keep the volume to less than 500 mm^3 to enable the phial to replace a standard mercury F.F.D. phial.

b) Dead Volume U

The experimental thermal systems made during this work had a typical dead volume of 60 mm^3. A realistic range of dead volume for this type of thermal system would be from 0 to 150 mm^3.

c) Capsule Diameter and Pressure Sensitivity

Capsules are generally made in traditional standard sizes, nominally ⅝, ¾, ⅞, 1 and 1½ inch, although the active diameter is normally slightly less than this. Therefore this study has been restricted to diameters of 15 to 35 mm. Particular emphasis is placed on the study of 18 mm diameter capsules as this was the size of a Harper Wyman capsule which seemed particularly suitable for development for gas filled F.F.D. use.

The pressure sensitivity is related to the diaphragm thickness and diameter and this relationship is discussed in section 8.3. However for the types of capsule likely to be suitable for these devices the pressure sensitivity would lie in the range from 10^{-9} to 5×10^{-9} m/Pa.

d) Fill Pressure P_f

The flexibility of the capsule and the maximum safe deflection put a limit on the maximum fill pressure, if the deflection limit is not to be exceeded during operation. For the thermal systems studied here, the fill pressures would be in the range 0 to 350 kPa absolute.

Figs. 53 to 57 show how the stroke or valve lift produced by gas filled thermal systems is affected by changes in the design parameters. To summarize it will be seen that thermal system performance increases as:-

a) Capsule diameter decreases
b) Phial volume increases

c) Fill pressure increases
d) Dead volume decreases
e) Starting pressure increases

Increasing the fill pressure to improve performance must be done carefully so as not to cause yielding of the capsule. Raising the starting pressure, for instance by restraining the capsule with springs, will give a useful increase in performance. This can be a valuable way to increase F.F.D. performance and is descussed fully in section 8.5.

8.3 Capsule Design and Performance

The capsule is the key component in the thermal system and in order to be suitable for a mass produced gas filled F.F.D., it must satisfy the following requirements:-

a) Have a high pressure sensitivity, with a reasonably linear performance over the range of operation.
b) Be cheap to manufacture
c) Have stable, elastic properties
d) Have a low dead volume in the relaxed state
e) Be resistant to corrosion

The 15 mm and 18 mm diameter capsules used by Harper Wyman for their mercury F.F.D. production were evaluated for use in a gas filled F.F.D. design. The resistance welded A.I.S.I. 302 stainless steel construction of these capsules made them relatively cheap to manufacture and endowed them with high corrosion resistance. Fig. 24 shows that these capsules also nested extremely well giving a low dead volume, approximately 25 mm^3 in the 18 mm diameter design.

The first choice to be made in capsule selection is that of capsule diameter. As fig. 53 shows, thermal system performance is reduced as capsule diameter increases, therefore the capsule diameter chosen ought to be small. However with diaphragms of 15 mm diameter or less, the number and depth of corrigations which can be produced is restricted and the top and bottom bosses start to occupy a large proportion of the diaphragm surface, resulting in an unsatisfactory capsule design. Therefore it was decided that the Harper Wyman 18 mm diameter capsule (figs. 23 and 24) offered most scope for development.

These capsules in their existing form had a mean pressure sensitivity which varied between 1.5 and 2.1 m/Pa (see section 7.2). This was fairly low and, as fig. 53 shows, a good performance gain can be expected if the capsule pressure sensitivity is increased. This is also true for non-linear capsules, as reference to figs. 30 and 31 will show that a more flexible capsule (fig. 31) gave approximately 0.06 mm extra stroke at 700 ^{o}C to one of two otherwise identical thermal systems.

The work of Wildhack et al (59) with N.B.S. type 1 diaphragms, has indicated the following empirical relationship between diaphragm pressure sensitivity and diaphragm thickness and diameter:-

$$\frac{EX}{(1 - \nu^2)\,D} = K\left(\frac{t \times 10^3}{D}\right)^{-\beta} \qquad \text{....... (8.1)}$$

where X is the mean pressure sensitivity (m/Pa), D is the diameter (mm), ν is Poisson's ratio, E is the elastic modulus of the diaphragm material (Pa), t the diaphragm thickness (mm), and β and K are constants. Although the equation was derived for a particular family of diaphragms, Newell (42) suggests that it could be applied to other diaphragm shapes with β ranging from 1 to 2, with a typical value of 1.5 (N.B.S. 1, β = 1.52 - see reference 59). In the experiment described in section 7.7, Harper Wyman 18 mm diameter capsules were thinned and $\bar{X}$, the mean pressure sensitivity, was compared to the diaphragm thickness. The results shown in fig. 38 demonstrate that the value of β for this type of capsule lies well within the range 1 to 2, with a most probable value of 1.5. Thus equation 8.1 with β set to 1.5 and K set to 415, can be used to predict the variation of $\bar{X}$ with thickness. The solid line on fig. 38 illustrates the nature of this variation for the 18 mm Harper Wyman capsule.

Due to the low pressure sensitivity of the standard 0.127 mm thick capsule, it is suggested that for gas filled devices the capsule thickness be reduced to 0.1 mm. From fig. 38 it will be seen that this would increase $\bar{X}$ to about 2.6×10^{-9} m/Pa. The wide spread of capsule pressure sensitivities has already been noted and if this range scales in the same way as $\bar{X}$ when the diaphragm thickness is reduced to 0.1 mm, then a sensitivity range of 2.1 to 2.9×10^{-9} m/Pa would be expected. These large pressure sensitivity variations are unavoidable in a mass produced capsule, as they are due to variations in the original thickness of the sheet metal used to make the diaphragms and variable thinning due to stretching during the pressing process (the unthinned samples 4b and 5b shown in fig. 38 illustrate the amount of thickness variation found in individual capsules). Also the corrugation shapes will tend to vary between capsules, due to the differing amounts of spring-back after pressing (due to the variations in the yield point of the strip used). However the capsule used to make F.F.D. number 31 had an $\bar{X}$ (measured using equation 7.2) of approximately 2.2×10^{-9} m/Pa and as this F.F.D had an acceptable performance (see section 8.5), then most capsules made using 0.1 mm thick diaphragms would have sufficient pressure sensitivity for a gas filled F.F.D.. Reduction of the diaphragm thickness to much less than 0.1 mm would not be very practical for mass production, as difficulty would be encountered in fabrication. In fact .075 mm is generally recognised to be the absolute minimum diaphragm thickness for practical capsules.

Reducing the diaphragm thickness may also help improve capsule linearity. Wildhack et al (60, 61) in their research with N.B.S. type 1 diaphragms found that a maximum linearity (for deflections up to 4% of diaphragm diameter) was achieved when the ratio of diaphragm thickness to diameter was 2×10^{-3}. Thicker diaphragms had a decreasing pressure sensitivity with increasing extension and thinner diaphragms tended to have an increasing pressure sensitivity with increasing extension (although for extensions greater than 4% of diaphragm diameter, the pressure sensitivity started to decrease rapidly with extension). Reducing the thickness of the Harper Wyman 18 mm diameter capsule to 0.1 mm would change the thickness to diameter ratio from 7×10^{-3} to 5.5×10^{-3}. Increasing the corrugation depth also increases capsule linearity (59, 42, 61) and the designer should attempt to make these as deep as the pressing process will allow. The comparison of the leading dimensions of the very linear inconel X 750 capsules made by Pressure Sensors Ltd. (pressure-extension curve shown in fig. 20) and the much more non-linear Harper Wyman capsule (see fig. 21 for pressure-extension curve) will help amplify the points made above.

CAPSULE TYPE	DIA. (D)	THICKNESS (t)	t/D x10^3	NUMBER OF CORRUGS.	CORRUG. DEPTH	CORRUG. LENGTH
H.W.	18mm	.127mm	7	4½	.22mm	1.7mm
P.S.	18mm	.075mm	4.2	2½	.32mm	2.1mm

More sophisticated design studies can be made using a finite element stress analysis technique, for which both the Battelle Memorial Institute (62) and Baxter (63) have developed computer programs. However, in view of the spread of capsule characteristics, their predictions will be no more accurate than those produced by simpler methods. The advantage of finite element analysis is in examining radical new diaphragm designs where little practical experience exists, or in the design of precision capsules.

Finally the diaphragm material must be chosen and in doing this two points must be borne in mind, the corrosion resistance and the maximum deflection required from the capsule. Obviously with diaphragms of only 0.1 mm thickness which are meant to last for at least 10 years, in what could well be a warm damp environment, any corrosion would be totally unacceptable. Therefore the chosen material must be highly corrosion resistant.

The maximum strain in the material of a diaphragm which is subjected to a deflection, is approximately proportional to the deflection expressed as a percentage of the diaphragm diameter.(61). The maximum stress in the material will be given by this maximum strain multiplied by its modulus and if this maximum stress exceeds the yield stress, then the capsule would suffer a "permanent set" (permanent deflection of the capsule). This is clearly undesirable and the capsule material and working range must be chosen to avoid this. A measure of the merit of a particular diaphragm material is therfore the ratio of the yield stress to the modulus (61) and the best materials would have a high strength/modulus ratio. Table 7 summarizes these properties for some commonly used diaphragm materials. The copper alloys listed in table 7, although having very good properties, can be ruled out for a mass produced capsule as they cannot normally be resistance welded. Soldering and brazing techniques, although very useful on a small scale, are diffucult to apply to capsule mass production. The most commonly used material for mass produced capsules is A.I.S.I. 302 stainless steel (or similar austenitic steel). This material is relatively cheap and readily available in diaphragm quality strip, however it cannot be hardened except by cold work. Thus material must be chosen which is soft enough to form into diaphragms, but which when formed, will be hard enough to confer reasonable spring properties to the diaphragm. It is for this reason that the Harper Wyman capsules are made from "½ hard" A.I.S.I. 302 strip, with a specified hardness range of H_V 220 to 290 and finished diaphragms would be work hardened (see section 7.9), to give a yield stress of about 800 MPa. Fig. 40 illustrates the results of permanent set tests on Harper Wyman 18 mm diameter capsules (see section 7.9). There was a significant amount of pre-stress in these capsules (caused by the top and bottom diaphragm being sprung against each other) and, as a previously unused capsule was taken to progressively higher maximum extensions, this pre-stress was reduced by yielding as indicated by the rise in the 138 kPa deflection reading. It will be noticed that as the maximum extension was taken beyond approximately 1.1 mm the yielding was sufficient to produce a permanent set, which increased rapidly with progressively larger extensions.

However this does not present too many problems, because if the capsule was initially extended to say 1.0 mm, then subsequent extensions below this maximum would cause very little extra yielding and the capsule performance would be reasonably stable. This gives rise to the process called "seasoning" (59), where capsules are pressurized to a deflection just beyond their working range so as to stabilize the pressure-extension characteristics. For the Harper Wyman 18 mm diameter capsules tested, it was found that one pressurization was sufficient to give good enough subsequent stability for gas filled F.F.D. purposes. As all capsules are pressure tested for leaks during the manufacturing process, the need for seasoning should cause no problems. Taking the capsule extension to beyond 1.1 mm however, would have a detrimental effect on it, as the large amount of permanent set would increase the capsule dead volume.

Table 7 indicates that 17-7 PH stainless steel would be a good choice of material for diaphragms. This material has all the advantages of 302 stainless steel, but can be precipitation hardened, enabling the diaphragms to be pressed from soft material and then hardened later. Some capsules with 0.127 mm thick diaphragms in this material were tested (section 7.9) and found to have good performance. When hardened, the typical permanent set after extension to 1.0 mm was between 0 and 0.06 mm (due to the heat treatment, there was no pre-stress to mask the permanent set), whereas the 302 steel capsules had a change in 128 kPa extension (the hidden permanent set) of around 0.1 mm. Also the 17-7 PH capsules were found to have a much lower hysteresis ($<$.005 mm) than the 302 capsules ($\sim$.03 mm).

These tests indicated that 17-7 PH was indeed a good capsule material (Trainer (62), recommends its use for bellows). The fact that softer material can be used for pressing the diaphragms, should enable a better diaphragm shape with deeper corrugations to be made.

8.4 Capsule Fatigue Life

When fitted to cooker ovens, a gas filled F.F.D. capsule would probably experience some 3,000 cycles in a 10 year life (29). This cycling has caused fatigue failures in mercury flame failure devices (see table 3 and 4) and there is a similar danger for the gas filled device. The work to determine how the fatigue life of standard Harper Wyman 18 mm diameter capsules was affected by different amplitudes of cyclic stressing is described in section 7.10. The results of these tests, in which capsules were cycled from a zero extension, are shown in fig. 43. It will be noted that out of the 61 capsules tested, none failed at below 15,000 cycles. Between 15,000 and 100,000 cycles there were 20 failures, all but one occurring when the capsules were extended to beyond 1 mm. The one failure which occurred at less than this cyclic extension was due to an edge weld leak.

Reference to fig. 43 shows that in the interval between maximum cyclic extensions of 1.118 mm and 1.168 mm there were a total of 8 failures and one "run out". Statistical analysis of the failures, assuming a log - normal distribution, enabled the number of cycles for a given percentage survival to be estimated with 95% confidence. The 95% survival cycle life was estimated to be 7,100 cycles and the 99% survival cycle life was 3,900 cycles. It is suggested that, because of the closeness of the 99% survival life to the expected working life, that capsules never be taken beyond 1.1 mm in cycling. For design purposes it would be prudent to assume a 1.0 mm maximum extension cycle as the limit, in order to give an additional safety factor.

The mode of failure was also very interesting. Classically capsule fatigue failures occur at the outermost corrugation (63), as this is normally the point of maximum cyclic stress. However by far the most common cause of capsule failure encountered (14 capsules failed in this way) was cracking of the top boss weld (see fig. 43). Fig. 44 shows a section through a cracked top boss weld and when viewed in conjunction with the complete capsule section shown in fig. 24, it will be appreciated that this weld is acting as a stress raiser, leading to early failure. Normally the stress raising effects of welds can be reduced by producing a weld with a 'fillet', however as economic factors dictate the use of a projection weld, it is difficult to see how this could be done. An improvement might be to reduce the top boss diameter, as due to the curvature of the extended diaphragm, this would reduce the stresses at the weld. Only one bottom boss weld failure was noted, believed to be due to the assymetric capsule design producing lower stresses on this weld.

Unfortunately no tests were conducted on 0.1 mm thick capsules because of lack of samples. However one 0.1 mm thick prototype was tested up to 100,000 cycles (between 0 and 1.002 mm extensions) without failure, indicating that a well made thin capsule should have a reasonable fatigue life.

When working as part of a pressurized thermal system the capsule would not be cycled between zero extension and a maximum value, but between some positive extension and a maximum extension. This is especially so in designs of F.F.D. in which the valve plate is attached to the top of the capsule, where the capsule is prevented from relaxing to its rest state and therefore the actual capsule movement is much reduced. The maximum capsule extension before occurrence of permanent set (see section 8.3) and the fatigue life data must therefore be taken in combination to produce guidelines indicating the working limits of a particular capsule, under these differing conditions.

The capsule must never be taken beyond the point where serious permanent set appears, i.e. the following condition must be adhered to:-

$$b + c < b_{max} \qquad \ldots\ldots\ldots (8.2)$$

where b is the static deflection (at the fill pressure), c is the amplitude of the cyclic deflection and b_{max} is the maximum extension before permanent set occurs.

When assessing the affect of mean stress on fatigue life, the Goodman law (64) is commonly used:-

$$\sigma_{an} = \sigma_n \left(1 - \frac{\sigma_m}{\sigma_u}\right) \qquad \ldots\ldots\ (8.3)$$

where σ_n is the fatigue strength for a given cycle life, σ_{an} is the stress amplitude for the same cycle life when a mean stress σ_m is also applied and σ_u is the ultimate tensile strength of the material. For a capsule, the material cannot be taken to its ultimate tensile strength as permanent set would be encountered, therefore it is suggested that σ_u is replaced by the yield stress (σ_u is approximately 1.25 x the yield stress for ½ hard A.I.S.I. 302 steel). As mentioned before the stresses in the capsule are approximately proportional to the capsule extension, therefore the stresses in equation 8.3 can be replaced by deflections to give:-

$$c \leq \frac{c_{max}\ b_{max}}{b_{max} - \frac{1}{2}c_{max}} \left(1 - \frac{b_m}{b_{max}}\right) \qquad \ldots\ldots\ (8.4)$$

$$\text{where} \quad b_m = b + \frac{c}{2} \qquad \ldots\ldots\ (8.5)$$

where c_{max} is the maximum cyclic deflection for a given percentage survival cycle life when cycling from zero extension, c is the maximum cyclic deflection for the same cycle life when a static deflection b is also applied and b_{max} is the maximum extension available without permanent set. Providing c is kept to less than, or equal to the function in equation 8.4, the capsule fatigue life will be greater than, or equal to that measured for c_{max}. In fact this guideline is very conservative as, due to the use of the yield stress, the allowable values of c will be less than those which would be predicted by the Goodman law.

Therefore, providing the capsule's operating extensions satisfy the conditions shown in equations 8.2 and 8.4, the fatigue life will be better than that measured for zero to maximum extension cycling. For the 18 mm diameter Harper Wyman capsules tested, b_{max} was 1.1 mm (see fig. 40) and the value suggested earlier for c_{max} was 1.0 mm. Therefore the operating conditions of these capsules must satisfy both of the following relationships.

$$b + c < 1.1 \qquad \ldots\ldots\ldots (8.6)$$

$$c < 1.83 - \frac{b_m}{0.6} \qquad \ldots\ldots\ldots (8.7)$$

In section 7.10 the "drift", or change in the pressure-extension performance, was measured for the standard 18 mm diameter Harper Wyman capsule over 100,000 cycles. In the test four capsules were cycled between zero extension and extensions between 1.033 and 1.062 mm, which it will be noted was just beyond the suggested limits for these capsules. The changes in performance measured were very small indeed, suggesting that providing these capsules are kept within the limits laid out in equations 8.6 and 8.7, they will perform reliably and repeatably for more than 30 times the anticipated cycle life.

8.5 The Gas Filled F.F.D.

Most domestic cooker ovens on the British market have a maximum consumption of 0.283 cubic metres (10 cu. ft.) per hour of natural gas. Gas flow ratings for valves were traditionally specified at 0.75 mb (0.3" w.c.) pressure differential. However the recent British Standard (13) has increased this to 1.0 mb differential. The 0.75 mb flow ratings are discussed here, but these are easily converted to 1.0 mb ratings using the following equation developed from equation 7.1:-

$$F_1 = F_2\sqrt{\frac{\Delta P_1}{\Delta P_2}} \qquad \text{.......} \quad (8.8)$$

where F_1 and F_2 are the flow rates at ΔP_1 and ΔP_2 pressure differential respectively. Therefore 0.75 mb ratings are converted to 1.0 mb ratings using:-

$$F_{1.0} = F_{0.75} \times 1.15 \qquad \text{.......} \quad (8.9)$$

The 0.75 mb pressure drop will be divided between the valve body and the valve seat (see section 7.1). Fig. 16 shows the pressure drop for a valve body with ¼" B.S.P. connections to be 0.09 mb at this flow rate. However the same valve body is also manufactured with smaller connections, therefore, including some safety factor, a pressure drop of 0.25 mb can be assumed for the valve body itself. When designing valve bodies, the pressure drop due to the body must be kept as small as possible, by making the gas ways as large as can be accomodated and by attempting to reduce all factors restricting the gas flow.

Fig. 17 shows the measured flow rate of natural gas past the standard 25 mm diameter valve plate and seat at different valve lifts (see section 7.1). Allowing 0.25 mb pressure drop for the body, leaves 0.5 mb pressure drop across the valve. At this pressure a valve lift of 0.132 mm is required to give a gas flow of 0.283 cubic metres per hour (see fig. 17). If a different valve plate diameter is desired, for instance to produce a higher flow rated F.F.D., the required valve lift would be:-

$$L = L_{25} \times \frac{25}{D} \qquad \text{.......} \quad (8.10)$$

where L_{25} is the valve lift obtained from fig. 17, and D is the diameter in mm of the valve plate. It will be noted that this design data only applies to the standard valve plate and seat as shown in fig. 18, but as this design has proved entirely successful there seems no reason to change it except for altering the diameter.

Appliances are sometimes fuelled by other types of gas such as L.P.G. and to a decreasing extent town gas. For these different gas "families", the flow rate through the valve at the same pressure drop can be obtained by modifying equation 7.1:-

$$F = F_N \sqrt{\frac{\rho_N}{\rho}} \qquad \ldots\ldots\ (8.11)$$

where F is the flow rate of gas with density ρ, F_N is the flow rate of natural gas and ρ_N is the density of natural gas. Table 8 gives densities of various fuel gases.

However this is not the complete picture as more or less gas may be required due to the different calorific value of the gases. This introduces the concept of the Wobbe index, W, of fuel gases (10).

$$W = \frac{C_g}{\sqrt{d}} \qquad \ldots\ldots\ (8.12)$$

where C_g is the calorific value of the gas and d its relative density. Therefore the heat throughput which will be passed by the F.F.D. when using a different gas is given by:-

$$H = \frac{W}{W_N} \cdot H_N \qquad \ldots\ldots\ (8.13)$$

where H_N is the heat throughput using natural gas and W and W_N are the Wobbe indices of the new gas and natural gas. Table 8 lists some Wobbe indices.

A thermal system must therefore be capable of producing at least 0.132 mm value lift (for a 25 mm valve) to be suitable for cooker ovens. Perusal of the design curves (figs. 53 to 57) showing the strokes produced by various thermal system designs would suggest that a gas filled thermal system ought to be able to produce sufficient valve lift. Indeed, this has been borne out by experiment and fig. 33 shows the flow performance of F.F.D. number 31 (with a 25 mm diameter valve plate), which was set to open at 325 °C. This valve was capable of passing approximately 0.4 cubic metres of gas per hour at 0.75 mb pressure drop, when the phial was heated to 700 °C - a very adequate performance.

The chosen F.F.D. opening temperature (T_s) determines the flow performance of the device. The opening temperature selected must be sufficiently high for the valve to shut within the time shown in table 5 when the maximum ambient temperature is encountered. Fig. 35 shows the cooling rate of a gas filled F.F.D. phial in an oven at maximum temperature and it will be noted that in the 90 seconds closing time allowed, the phial had cooled to 215 °C. Thus allowing for some safety factor, the opening temperature of a F.F.D. ought to be in the range 275 °C to 300 °C, although each appliance application must be individually checked. It is clear from the nature of the thermal system performance curves (e.g. fig. 31) that the lower the opening temperature, the greater the flow performance. Therefore for applications where low ambient temperatures are encountered, the opening temperatures should be reduced, perhaps down to 200 °C (see the room temperature cooling curves on fig. 25).

F.F.D. opening times must also be within that specified in table 5 (90 seconds for domestic ovens), when heated by the small bypass flame on the main burner (see section

3.2.1), or a pilot (see section 3.2.2) and usually the main burner bypass flame causes most problems. However, experience with gas filled F.F.D. phials has shown that providing they are positioned correctly, they will be heated by a bypass flame to 300 ^{o}C in approximately 10 seconds and reach a stable temperature of around 500 ^{o}C after one minute. Thus opening times should present no problems.

The 500 ^{o}C running temperature in a bypass flame would give a 0.75 mb flow rating of 0.23 cubic metres per hour for experimental F.F.D. 31 (see fig. 33), but dropping the opening temperature from 325 ^{o}C to 275 ^{o}C would give a rating in the region of 0.28 cubic metres per hour at 500 ^{o}C. However once the F.F.D. opened partially, the positive feedback effect of the increased flame size would open the F.F.D. fully. Normal phial temperatures encountered in burner flames once the F.F.D. has opened are in the region of 600 ^{o}C to 700 ^{o}C. Pilots present no problem, as even a very small flame can be arranged to heat a phial to 700 ^{o}C.

The experimental F.F.D.'s produced during the present research (e.g. F.F.D. 31, fig. 33) proved that a gas filled F.F.D. can have the required performance for a domestic oven application. Therefore it is envisaged that a production version of the gas filled F.F.D. would not be very different from the experimental devices made for this work. The choice of a 500 mm^{3} phial is recommended for a production version, as this is not over large and gives an adequate performance. If the design requires a different sized phial, fig. 54 gives some indication of the change in thermal system performance to be expected. As was stated in section 8.3, a 0.1 mm thick capsule if recommended for a production device, rather than the 0.127 mm thick capsule used to make F.F.D. 31. However the capsule used in F.F.D. 31 was selected for high pressure sensitivity and represents the expected minimum flexibility of 0.1 mm capsules. Therefore the performance of F.F.D. 31 (fig. 33) represents the minimum to be expected from flame failure devices with 0.1 mm capsules. The effect of capsule pressure sensitivity on F.F.D. performance can be gauged from the design curves.

The fill pressure chosen should be as high as possible to give the maximum performance (fig. 55), but should not take the capsule beyond the working range specified in sections 8.3 and 8.4. Here the 1,000 ^{o}C phial temperature test required by BS 6047 must be taken into account, however this should present no problem, due to the constantly reducing gradient of the phial temperature-stroke curve. In service no temperature greater than 850 ^{o}C would be encountered, even with a maximum aeration gas flame. Designs should also aim at minimising the dead volume, by using a well nested capsule and a very small bore capillary tube.

Finally there is a choice of several modes of construction. The valve could be actuated via levers, although expensive, this would be useful where a high flow performance was required. The main choice lies between the attachment of the valve to the top of the capsule, as in fig. 32, or the use of a spring to hold a separate valve plate on its seating, as in the standard mercury F.F.D. shown in fig. 5. Both methods have advantages and disadvantages, some of which are listed below:

<u>Attached valve plate - advantages</u>

a) Does not require a spring

b) The valve plate does not move relative to the valve seat, so the rubber seal will "bed in" properly

c) Easier to assemble in production, as the valve plate simply has to be screwed onto a fixed stud.

Attached valve plate - disadvantages

a) The stud fitted to top of capsule must be perpendicular and concentric to the capsule

b) Possible extra stress on the weld fixing the stud to the top diaphragm, lowering the fatigue life

Separate valve plate - advantages

a) Useful performance increase due to the spring pressure

b) Construction similar to the mercury F.F.D.

c) Tolerances on the top boss fixing much wider than with attached valve plate designs

Separate valve plate - disadvantages

a) Extra cost of spring

b) The valve plate will tend to rotate and not bed into the seat so well

c) There is a possibility of wear between top boss and valve plate adjustment screw. This would affect the calibrated opening temperature of the F.F.D.

Both methods are practical, and it is up to the manufacturer to decide which method suits the prevailing circumstances best.

The chance of increasing performance by restraining the capsule with a spring force was noted earlier and the method of construction with the valve plate held down by a spring clearly lends itself to this. The pressure effective area of a Harper Wyman 18 mm diameter capsule has been measured at 0.992×10^{-4} square metres (see section 7.8) and this can be used to convert the spring force to a starting pressure (P_s). Fig. 57 illustrates how increasing P_s improves thermal system performance.

A fairly stiff spring of 10N force would give a P_s of 101 kPa and for F.F.D. 31, computer predictions indicated that this would improve the capsule stroke between 300 ^oC and 700 ^oC from 0.196 to 0.241 mm, a very worthwhile performance improvement. However increasing spring forces too much could cause problems due to valve seal creep (see section 8.7). If ways could be found to incorporate high spring loads, without also causing creep problems, then as fig. 39 shows, capsules can withstand loads of at least 20N without change in the pressure effective area. If a 20N load were applied to F.F.D. 31, the 300 ^oC to 700 ^oC stroke would be improved to 0.28 mm. This would be equivalent to a flow rate of approximately 0.5 cubic metres per hour at 700 ^oC (when T_s = 300 ^oC) and a full flow of 0.28 cubic metres per hour would be achieved at 450 ^oC (compare to fig. 33). The springs chosen to load the capsules must have a low rate, as an increase in loading with capsule stroke would reduce the expected performance gain. With this proviso, it will be seen that a spring can be used to produce a valuable performance increase in a gas filled F.F.D. design.

8.6 The Variation of F.F.D. Performance with Ambient Conditions

As might be expected with a gas filled device, variations in ambient temperature and pressure will considerably affect the opening temperature of the valve. Program var.basic (see section 5.4.2) was written to investigate the variation of opening temperature (T_s) with ambient conditions and fig. 58 shows the results for F.F.D. 31 with no temperature compensation. The rectangle A-B-C-D on fig. 58 indicates the range of conditions which might be encountered in the U.K. and it will be seen that under extreme circumstances, the opening temperature is likely to drop from 325 ^oC to 250 ^oC.

This amount of reduction in the opening temperature cannot be tolerated in a practical F.F.D., however temperature compensation is easily achieved, since most rubbers have very high thermal expansion coefficients - typically 2.5 to 4 x 10^{-4} per degree C for silicone rubber (65). The high expansion of the rubber seal can be used to compensate for ambient temperature effects. The standard silicone rubber valve seal was found to expand by 5.3 x 10^{-4} mm per degree C (see section 7.13), equivalent to a linear expansion coefficient of approximately 3.8 x 10^{-4} per degree C. Fig. 59 illustrates the variation of T_s with ambient conditions for F.F.D. 31 with a temperature compensation provided by a valve seal expansion of 7 x 10^{-4} mm per degree C. It will be seen that this was the ideal amount of compensation for this particular F.F.D.. Under the most extreme U.K. conditions, the opening temperature would only fall from 325 $^{\circ}$C to about 300 $^{\circ}$C, which would be of no consequence under normal operating conditions. If sold to other countries, the F.F.D. may well be used at altitude and fig. 59 indicates the reductions in atmospheric pressure encountered at different altitudes.

To obtain the correct temperature compensation the thickness of the valve seal (dimensions A on fig. 18) would have to be changed. For F.F.D. 31 the thickness would need to be increased to 1.32 mm.

8.7 The Anticipated Life and Reliability of the Gas Filled F.F.D.

The long term tests (section 7.12) indicated that the life of a well made gas filled F.F.D. could be very long indeed. Four samples survived for longer than 3,200 hours in a continuous flame and four samples exceeded 30,000 cycles on a cycling burner. The three failures, as was explained in 7.14, were due to the shortcomings in the construction of the experimental F.F.D.s.

One of the factors limiting F.F.D. life would seem to be phial metal wastage, due to oxidation and/or carburization by the gas flame. However for the samples tested on a continuous gas flame, the amount of metal wastage observed after 3,600 hours at 700 °C was insignificant. Therefore the life of a 0.5 mm thick A.I.S.I. 304 phial under these conditions is expected to be very long, probably much greater than 10,000 hours. Cycling conditions, as would be expected, produced much accelerated phial wastage. Approximately 0.1 mm of metal was lost after 40,000 2½ minute hot, 2½ minute cold cycles between 700 °C and 75 °C. Thus a 0.5 mm thick phial would certainly outlast 100,000 such cycles. Domestic oven operation would lie between these two extremes, with approximately 3,000 hot cycles in 10 years, of average duration between perhaps one and two hours. However the indications are that a 0.4 or 0.5 mm thick A.I.S.I. 304 phial would easily outlast this life. The 6,000 cycle BS 6047 test (see section 5.1) would clearly present no problems for a well made gas filled F.F.D..

No failures in the life tests could be attributed to capsule fatigue and providing the capsule stressing guide-lines in sections 8.3 and 8.4 were adhered to, domestic oven service should present no problems. One worry was that the low partial pressure of oxygen encountered in a thermal system might cause fretting of the capsule, however no sign of this was noticed on the samples which were subjected to burner cycling (see section 7.14).

One important requirement of BS 6047 was that if broken, a F.F.D. must always fail safe. The gas filled F.F.D. will be better than the mercury F.F.D. in this respect, as the chance of a blockage resulting in the capsule remaining pressurized is much reduced. The method of construction with the capsule attached to the valve plate will be very good from this point of view, as the loss of fill pressure will cause the capsule to pull the valve plate down onto its seating with extra force.

To be reliable a F.F.D. should keep close to its calibrated opening temperature throughout its life. However creep of the rubber valve seal under the valve sealing force provided by the capsule or spring would gradually reduce the opening temperature. Fig. 49 shows the creep of standard valve plates under a 10N load at different temperatures and indicates that after a settling period of approximately 1 hour, a creep rate of up to 0.0085 mm per log decade can be expected. It will be seen that this creep rate was not affected very much by temperature, illustrating the usual finding that the creep rate of rubber follows the same pattern at all temperatures, the only difference being that the log time scale is shifted (66).

It is suggested that F.F.D.s are calibrated to give the required opening temperature after they have been shut for a given period - say 10 hours. After this the rate of creep against real time will be slow. For instance under a 10N load the standard valve plate will have compressed by a further 0.034 mm from its 10 hour compression after 10 years of service. For F.F.D. 31 this would be approximately equivalent to a reduction of 40 ^{o}C in the opening temperature.

The creep rate is usually proportional to the amount the rubber is compressed (66), which as fig. 46 illustrates is linearly related to the load applied. Therefore the lower the valve sealing force the less the creep rate and if necessary a low creep valve could be made using the separate valve plate method of construction with a very light spring. For a F.F.D. with the valve plate attached to the capsule, the valve plate sealing force is fixed and can be calculated using the following equation developed from equation 5.12:-

$$F = A_e \left\{ 101.3 + P_r - \frac{P_n \, T_e^2 \, (V_p + U)}{T_e \, 300 \, (V_p + U + \tfrac{1}{2}\pi r^2 b)} \right\} \quad .... \; (8.14)$$

Normally when the valve is fully shut, $T_e \sim 300\ ^oK$, therefore equation 8.14 can be simplified as follows:-

$$F = A_e \left\{ 101.3 + P_r - \frac{P_n \, (V_p + U)}{V_p + U + \tfrac{1}{2}\pi r^2 b} \right\} \quad .... \; (8.15)$$

where P_r is the pressure read from the capsule pressure-extension curve at the capsule extension, b, at which the valve shuts and A_e is the capsule pressure effective area. All the other variables are as defined in section 5.3. This equation gives the valve sealing force for F.F.D. 31 as approximately 10N.

8.8 Manufacture of the Gas Filled F.F.D.

Because of the similarity of the gas filled F.F.D. to the mercury F.F.D., very little change to the mercury F.F.D. production plant would be necessary to enable the gas filled F.F.D. to be manufactured. The only major change needed would be to the filling equipment for the thermal systems.

Fig. 60 illustrates the phial shape envisaged for a production F.F.D. and suggests a filling method. The phial and capillary are made separately and then brazed together, since this is far cheaper than a one piece construction. After brazing it is suggested that the assembly is heated to say 700 ^oC in a furnace to drive off all contaminants such as brazing flux and oil from the inside of the phial. The capsule would then be brazed to the capillary and the open phial end inserted into the filling rig as shown in fig. 60. After evacuating the thermal system is filled to the correct pressure with helium and sealed by means of the two 'chisel' spot welder electrodes. The swaged down phial end is necessary for a good quality spot welded seal, as experience has shown that it is very difficult to seal large diameter tube in this way. For mass production purposes it is suggested that many thermal systems be filled at once by fitting them onto a rotary table. They could all be evacuated and pressurized simultaneously and then each thermal system could be swung beneath the spot welder electrodes for sealing.

Having been sealed, the thermal system would then be stroke tested by heated the phial in a flame and checking the movement of the capsule. If the stroke was within the correct limits the thermal system would then be fitted to a valve body. After this, the method of manufacture and testing would be very similar to that for existing mercury production.

CHAPTER 9

THE MARKETING CHANNEL FOR F.F.D.'S

9.1 The Theory of Marketing Channels

The F.F.D. manufacturers do not sell direct to the public, therefore an industrial marketing channel exists. This is a group of organizations who pass the product from one to another, until it is eventually bought from the last channel member by the "end user". Fig. 61 shows how the marketing channel for cooker F.F.D.'s is organized.

The distribution of power (and perhaps more importantly PERCEIVED power) in the channel is crucial, as it determines just how free each member is to make product, marketing and pricing decisions. Rosenbloom (67) considers that the basis for power in the market channel can be of 5 different types:-

1) Reward power
2) Coercive power
3) Legitimate power
4) Referent power
5) Expert power

He defines each of these as follows:

Reward power. The capacity of each channel member to reward another if the latter conforms to the influence of the former.

Coercive power. Essentially the reverse of reward power. In this case a channel member's power is based on the expectation that the former will be able to punish the latter if he fails to conform to the former's influence attempts.

Legitimate power. This power base stems from internalized norms in one channel member, which dictate that another channel member has a legitimate right to influence him and that he has an obligation to accept that influence.

Referent power. When one channel member perceives his goals to be closely allied to, or congruent with, those of another member, a referent power base is likely to exist. Thus a channel member will find it easy to influence another member whose interests are very similar to his own.

Expert power. This base of power is derived from knowledge (or perception of knowledge) which one channel member attributes to another in some given area.

Another important factor determining interorganizational relationships in the marketing channel is the concept of "role". Rosenbloom (67) defines role as "a set of prescriptions defining what the behaviour of a position member should be". The role of each member will be closely associated with his own interests, thus the role of the F.F.D. manufacturers would be to increase the market share of their own particular brand of F.F.D.. Aside from such clear cut isssues, there is a grey area where interests overlap or conflict. In this case the roles of channel members could be defined when the channel is set up, or could develop with time. Many channels are very old (the F.F.D. channel ~15 years) and over the years channel conflicts develop, where members seek to change their role. The outcome of these conflicts will probably depend on the power distribution in the channel, but with time each channel member's "role perception" begins to coincide with his colleagues "role expectations" of him. Thus Ford (68) has found that "the role expectation structure is more clearly visible in long established channels, and the rigidity of member expectations increases with time" and that "expectations eventually tend to become governed by a code of ethics based on established practice".

9.2 The F.F.D. Channel

Ford (68) has studied the channel for gas central heating appliances and has attempted to measure the balance of perceived power in this channel. Members of each channel level were questioned and a value assigned to the power attributed by the respondents to each channel level. The net power between two levels A and B was then calculated by subtracting the power of A over B from that of B over A. Fig. 62 shows the results from the point of view of each channel level. The arrows indicate the direction of the net power. These results are interesting, as all perceived the Gas Board to have net power over each level.

Fig. 62 should now be compared with fig. 61, the marketing channel for domestic cooker F.F.D.'s as it was in 1977. It will be observed that British Gas is actually a member of the last level of this channel, as it sells gas appliances through its gas showrooms. In fact it will be noted that the gas showrooms virtually monopolise the last channel level, as in 1977 they accounted for 91% of cooker sales. The situation for other gas appliances is much the same and for instance in 1979 sales through British Gas showrooms accounted for 88.5% of cooker sales, 86% of space heaters and 67% of instantaneous hot water heater sales (69).

Thus referring to Ford's power measurements, it will be appreciated that the power of British Gas in this channel will be greatly enhanced when compared to the central heating channel. This is because as well as having the same outside influence on the channel, it has extra power bestowed upon it by its virtual monopoly of the bottom channel level and as fig. 62 shows, this is one of the most influential positions in the whole channel.

The high percentage of cookers retailed through British Gas gives it an enormous reward and coercive power base, which is made full use of. Any appliance must be "sales listed" before it can be sold through a British Gas retail outlet, thus the consequences of a "sales listing" refusal for a product are obvious. To obtain "sales listing", an appliance must be submitted to British Gas for a safety and engineering evaluation. The appliance must contain only "approved components", thus British Gas by virtue of its channel dominance can control even the component manufacturers producing F.F.D.s. British Gas maintain that this situation is very much for the public good, as being the supplier of gas, it must exercise responsibility for safety, and "there cannot in the Corporation's opinion be a clear cut distinction between research into appliance development and research into gas safety". (69)

9.3 The Investigation by the Monopolies and Mergers Commission

On December 1 1977 the Director General of Fair Trading requested that the Monopolies and Mergers Commission examine the supply of cookers, space heaters and instantaneous hot water heaters for the existence of a monopoly situation (70). The Commission published its report in August 1980 (69) and one of the conclusions reached was that the British Gas Corporation had a monopoly of the supply of these goods to the public. The Commission recommended that the British Gas Corporation's retail outlets should either be sold off to the public sector, or the accounting proceedures should be changed to prevent the Corporation from using its monopoly power in appliance marketing.

The Commission criticised the appliance manufacturing industry for its lack of investment in buildings and production plant and its failure to develop a significant export market. The report (69) stated, "This seems to stem chiefly from the dominant position of the B.G.C.. This is exercised in the first place as a monopoly buyer and retailer, but the Corporation has additional weight as the statutory monopolist supplier of the fuel. It is therefore in a position to exercise a strong influence over appliance design and manufacturers have found themselves obliged to comply with the Corporation's wishes as to the type of models produced, their design characteristics and their promotion. It is our impression that the manufacturers - even those which form parts of groups with substantial manufacturing involvement in other fields - have come to rely too greatly on the Corporation for research and development, basic design, market research and marketing, so that their own activity in these fields is now inadequate for the nature of the goods, and the changing demands of the final customer".

From this it is evident that besides having a reward and coercive power base, British Gas also has legitimate, and expert power base. It is also clear that the Corporation has a referent power base, as the success of the manufacturers depends upon the ability of the B.G.C. to market the appliances they make.

What then will happen to the market channel if, as the Monopolies and Mergers Commission recommends, the British Gas retail outlets are removed from its control? Ford (68) has shown that in long established channels, members' role expectations become rigidly fixed and thus any changes would be expected to be slow. Also Ford's examination of the gas central heating channel, where British Gas do not act as a retailer, (builder's merchants do this), has shown that the Corporation still has a very strong influence. Thus if the Corporation lost its retail outlets, its Reward and Coercive power bases would be diminished, but the Legitimate, Expert, and Referent power bases would still exist. This combined with the fixed role expectations in the channel would tend to suppress any dramatic change.

CHAPTER 10

THE F.F.D. MANUFACTURING INDUSTRY

10.1 Structure of the F.F.D Manufacturing Industry

Fig. 61 illustrates the structure of the gas cooker F.F.D. manufacturing industry as it was in 1977. There were three major manufacturers in competition, Harper Wyman Ltd (part of the American group Oak Industries), Teddington Controls Ltd (part of the British group United Gas Industries) and Concentric Controls Ltd. There were also two other minor manufacturers, T.I. Gas Controls Ltd, who made F.F.D.'s for the T.I. range of gas cookers from parts supplied by Harper Wyman and Drayton Controls Ltd, who made F.F.D. thermal systems only. Fig. 61 gives the relative market shares of these companies (except for Drayton, which had a very small market share). All were involved in making other types of gas controls such as thermostats and gas cocks, as well as manufacturing F.F.D.s.

The majority of the F.F.D.'s made by these companies are of the mercury type, which has as yet suffered from very little import competition. The mercury F.F.D. is not used in Europe and consequently the European manufacturers have no production capacity for the manufacture of this device. The U.S.A. however, has a large mercury F.F.D. industry, the market leaders being Robertshaw, White-Rogers and Harper Wyman.(the U.S.A. parent company), but as yet there have been very few imports into the U.K. from these sources.

Although British domestic cookers are mainly fitted with the mercury F.F.D., most other appliances use thermoelectric F.F.D.s. The thermoelectric device is manufactured widely on the continent and British manufacturers have suffered intense low priced competition from Spain (Copreci), Italy (S.I.T.) and Germany (Junkers). The British industry has now found itself unable to compete on price terms and at present almost 100% of the thermocouples and coils for thermoelectric F.F.D. assemblies are imported.

10.2 The History of Harper Wyman Ltd

This company began just after the war as Star Engineering Ltd and manufactured a variety of gas taps. In the mid-1960's this company was acquired by the American manufacturer of gas controls, Harper Wyman, who wished to use Star as a vehicle for marketing its designs of thermostat and F.F.D. in the U.K. Expertise and manufacturing equipment were sent from the United States and Harper Wyman Ltd (as Star eventually became) was amongst the first U.K. manufacturers of mercury F.F.D's. During the early 1970's, the American parent company was acquired by Oak Industries Inc., a large American conglomerate with investments in a wide range of industries and Harper Wyman Ltd was consolidated into the Oak Group accounts. Oak Industries already owned another British manufacturer, Diamond H Controls Ltd, a company which manufactured electric controls such as relays, thermostats, and "simmerstats" for electric cookers. The two British companies were not closely associated, despite their common ownership, although Diamond H did manufacture some parts for the Harper Wyman thermostat.

Harper Wyman Ltd had gradually expanded during the 1970's from a total sales value of £135,000 in 1971 to £1,250,000 (approximately £656,000 at 1971 prices) in 1979. However company profitability remained low, so in 1980 Oak Industries decided to rationalize its U.K. operations, by closing down the Harper Wyman factory at Malvern Link which employed approximately 100 people, and transferring production to the much larger Diamond H facility at

Norwich which employs approximately 1,000 people. As the Diamond H name was not well known in the gas industry, the Harper Wyman name was to be retained for the gas controls produced by Diamond H.

CHAPTER 11

THE MARKETING STRATEGY OF HARPER WYMAN

11.1 Distinguishing Features of Industrial Marketing

Webster (71) has stated that the "hallmark" of industrial marketing is a close buyer-seller relationship, unlike consumer marketing, where these relationships are brief and more often than not end with the sale. In an industrial marketing situation the buyer depends upon his supplier for an assured supply of components of the right quality and price, with efficient order handling and delivery. Getting all of these components of the deal right requires much negotiation, and a continual relationship between buyer and seller. Thus to quote Webster, "the actual transaction is only one point on the time continuum in industrial marketing" (71). It is clear then that the buyer is not looking for just a product from his supplier, but a service as well, thus effective selling in industrial markets depends upon all parts of the organisation (e.g. the manufacturing, research, development, inventory control and engineering departments) working efficiently together, hence industrial marketing is marked by its greater "functional interdependence" than consumer marketing.

Industrial buyer behaviour is considerably different from consumer behaviour and in developing a marketing approach this must be taken into account. The industrial buying decision making process is a complex one, as it involves many people, complex economic and technical factors must be considered in detail and the formal organisation within which the buyer works has an influence. Because of these factors, industrial buying decisions take a long time and need much consulatation, thus the selling organisation must expect to put in a lot of marketing effort and then expect a large time lag before any buyer response.

Finally the product itself is more complex than in consumer marketing. Webster has stated, "the product is not a physical entity per se. Rather the product is an array of economic, technical and personal relationships between the buyer and seller". Thus the marketer must be willing to discuss with the potential customer and if necessary change the product and the terms under which it is offered to suit the customer.

11.2 Development of a Marketing Strategy

A corporate strategy must be developed to enable a company to make a consistent approach to marketing itself and its products. Webster (71) has suggested that any strategic planning process should have the following seven components:-

a) An appraisal of the strengths and weaknesses of the firm.
b) The creative definition of the firm's distinctive competence.
c) An assessment of the economic market environment and how it is changing.
d) The definintion of long-term goals.
e) The identification of specific market and product opportunities available to the firm, given its capabilities, and the selection of those to be persued.
f) The setting of specific, measurable objectives required to achieve long-term goals.
g) The development of programs for exploiting defined opportunities and meeting those objectives.

A strategic plan should allocate a company's resources such that the maximum use is made of the strengths in the organisation and so minimum exposure is given to its weaknesses. Clearly such a planning exercise will also define areas to which the company should commit resources so as to improve its capabilities.

11.3 Marketing at Harper Wyman Ltd

The Marketing Director at Harper Wyman considered that the main strength of the company was its ability to change its products to meet its customers needs and that this had made a major contribution to the company's sales. In his opinion both major competitors (Concentric and Teddington) were not so flexible and tended to offer standard products on a "take it or leave it" basis. This strategy of flexibility was incorporated into the company structure, when in 1978 the marketing director also took on responsibility for new product development. It was considered that this would give increased efficiency in converting customers' needs into new or modified products.

Selling was conducted very much on a personal relationship basis solely by the marketing director. He considered that this was possible because the company only dealt with a total of approximately 40 regular customers (only one of whom purchased F.F.D.'s) and about 12 peripheral customers. Of the regular customers, one (Valor) accounted for 22% of the company's sales. The director attempted to visit each customer at least once per year. Some exporting was done by the company and one notable achievement was the exporting of refrigerator gas taps to Electrolux of Sweden. It had taken Harper Wyman six years with many visits and quotations before it was accepted as an established supplier. This example was very much the exception, as in general little effort was put into export marketing.

Most customers operated with very low stock levels and for example Valor operated with one month's supply of parts while Potterton worked on the basis of only three day's supply. To facilitate the efficient handling of customers' orders, works scheduling, and delivery, Harper Wyman installed a new mini-computer based stock control system in 1980, however the company closed before this new system had realised its full potential. The majority of customers preferred to double or triple source when buying F.F.D.s and thus interchangeability between the different manufacturer's products was an important customer requirement. Unfortunately whilst the products of Concentric or Teddington were directly interchangeable, the Harper Wyman F.F.D. had a differently shaped phial requiring a different fixing. Because of this, direct F.F.D sales made by Harper Wyman had dropped from 13% of the market in 1977 to only 6% in 1979, and in fact most production went to Valor which single sourced from Harper Wyman. Thus F.F.D.s had been "squeezed in significance" and the importance of F.F.D.'s in relationship to the company's other products can be gauged from the following table of sales values for 1979.

PRODUCT	TOTAL SALES VALUE (1979)
Thermostats	£570,000
F.F.D.s	£ 80,000
Gas Cocks	£500,000
Central Heating Valves	£100,000 (Source Harper Wyman Ltd)

The marketing director recognised that the phial shape was limiting the sales of an otherwise good product and in his new role as director of new product development initiated the design of the "mini-bulb" F.F.D. which was directly interchangeable with the competition's products. It was hoped that his new product would produce a considerable rise in the Harper Wyman share of the F.F.D. market, but the company closed before this new product could get into production, although production of this device is now being taken up by Diamond H Controls Ltd.

11.4 Analysis of Harper Wyman Marketing Strategy

It is instructive to examine the corporate strategy of Harper Wyman in the light of Webster's seven point planning process. (See section 11.2).

The basic strength of the company was its ability to machine small metal parts and assemble them into finished valves. Harper Wyman had two main weaknesses, the first of which was that there was only one draughtsman and one one non-graduate engineer to assist the marketing manager in the product development programme. The other weakness of the company was the age of the production plant which tended to preclude high productivity manufacturing methods. Since the original equipping of the factory to make F.F.D.s, the American parent company had allowed little investment in the factory.

The marketing director had identified the company's "distinctive competence" (defined by Webster as "a product-market strategy which distinguishes the firm from its competitors in some way important to its customers") as "flexibility", meaning that Harper Wyman was willing to modify its products (e.g. modifying F.F.D. valve bodies to suit customers' requirements) to meet customer requirements. However such a marketing approach would put greater strain on the development department due to the higher work load, and the fact that due to "functional interdependence" the development department would be in the "front line" of the marketing effort. Despite the fact that this marketing strategy highlighted the small amount of development effort available, the marketing manager was convinced that the "flexibility" strategy contributed to sales.

When considering mercury F.F.D.s the "assessment of the market environment and how it is changing" revealed two things. The first was the need for a product which was interchangeable with its competitors to restore the eroded market share and the first "goal" was the introduction of such a product. Unfortunately due to the reduced significance of F.F.D.s in Harper Wyman's output, limited design effort had to meet higher priorities (such as thermostat development) first, so the new design was slow in coming to fruition, allowing the Harper Wyman market share to drop as low as 6%. In the longer term there was the prospect of British Gas banning mercury F.F.D.s. Here was the threat of the loss of £80,000 per annum production, (more if the new F.F.D. succeeded), but the opportunity of a much larger production if an acceptable alternative to the mercury F.F.D. could be developed. The company could not afford to commit scarce financial and design resources to such a high risk venture, so the project was "farmed out" to Bath University, leading to the present research. The "measurable objectives" of this programme would be the development of a mercury-free F.F.D., acceptable to both British Gas and the customer. Finally the "programme for exploiting defined opportunities" would be the production and marketing of the mercury-free F.F.D. if it proved acceptable.

Turning now to buyer-seller relationships, it was outlined in section 11.1 that industrial marketing is marked by the closeness of buyer-seller relationships, thus successful industrial marketing must require a great amount of marketing effort on the part of the seller. With 40 regular customers to look after, the Harper Wyman marketing manager would need all of his time to maintain regular contacts (he tried to visit customers once per year), as well as looking after his new product development responsibility. The development of new buyer-seller relationships especially in the export markets, is an extremely time-consuming process and the marketing director would have little time for the regular contacts and follow up needed. Thus the company had little commitment to developing new markets, especially in the export field.

However as noted in section 10.2, Harper Wyman Ltd (Malvern Link) closed down in 1980 and although there were some rationalization reasons for this decision, the main reason was that the profitability of the company did not justify its continued existence. The major cause of this, in the opinion of the author, was the failure of the company marketing strategy to develop sufficient market share to keep unit costs down. It has been noted how the share of the F.F.D. market had fallen from 13% to 6% and this would increase unit costs tending to depress market share even further. The antiquity of the production plant, although causing occasional quality problems and needing extra staff to run and maintain it was of secondary importance as a cause of the company's failure. This was because the costs of the plant had been written off long ago and the introduction of new machinery would have demanded large improvements in productivity to pay for it.

The way out of this downward spiral was to develop new products and new markets, but as has been pointed out, doing this needed high quality technical personnel and more marketing manpower, which the company did not possess. In developing new products for the gas industry the situation was made worse by the safety and engineering evaluation required by British Gas which lengthened new product development times and took up the time of technical staff. Clearly extra technical staff and to a lesser extent more marketing effort was required, but the necessary personnel needed would have to be of high quality and therefore expensive. Unfortunately the pay-off time from this manpower investment would have been long and no financial help was available from Oak Industries. Possibly the only was out of the situation would have been a reduction in the production staff by streamlining the production operation and using the salaries saved to pay for the technical staff needed for product development. This was not done and the management's failure to make the employment of high quality development engineers a high priority, plus their choice of a marketing strategy which highlighted the company's weakness, must be regarded as a major factor in the failure of the company.

CHAPTER 12

MARKETING THE GAS FILLED F.F.D.

12.1 The New F.F.D. - Success or Failure?

The chances of a new product succeeding in the market place are very low. Cooper (37) states that in 1974 an estimated 30,000 new products were introduced onto the American market, but of these, 80% were not on the market one year later. Booz, Allen and Hamilton (72) have shown that for every 6 man hours spent on industrial R and D, 5 of these hours were spent on products that failed or were cancelled.

In an ideal world, it would be possible to identify in advance products which would succeed. This of course is not possible, but new products can be examined with respect to marketing theory and the conditions prevailing in the market place to identify those which have a higher probability of market success.

Much research has been done to identify just what separates new product failures from successes and many different parameters have been identified which could be important. Cooper in his "project Newprod" (37, 38) found 18 "dimensions" which characterised new product projects. When related to new product outcomes, it was found that there were three "dominant" dimensions, which were a determinant of new product success. These were:-

1) Product uniqueness - superiority

2) Market knowledge and marketing proficiency

3) Technical and production synergy - proficiency

Cooper analysed almost 200 new products, half of which were successes and half of which were failures. He found that of the new products which were "high" on all three factors (see above), 90% were successes and for new products with a "low" rating on all three factors only 7% could be classed as successes. Moreover Cooper discovered that these three factors were important determinants of success "regardless of the type of venture or type of firm".

Because of this it is instructive to analyse the new F.F.D. project with regard to these three factors. Firstly considering "Product uniqueness - superiority", the device developed in the present work would clearly have the advantage in the customers' eyes of being like the mercury device, but without the problem of mercury and at the present time this F.F.D. is unique in that there are no other devices offering this advantage. "Technical and production synergy - proficiency" brings in the question of the abilities of the company intending to produce the product, which in this case would be Diamond H Controls Ltd, as the successor to Harper Wyman Ltd. Diamond H has a long history in the production of small components for the electric cooker industry, in particular one of their products, the electric cooker thermostat, is very much like the new F.F.D. as it contains a capsule - phial thermal system.

In fact Diamond H, unlike Harper Wyman Ltd., has a facility for the production and welding of nesting capsules and has much experience in this area. Furthermore, since Diamond H has now taken over mercury F.F.D. production from Harper Wyman, the company will have gained more experience in the production of these devices by the time the new F.F.D. is ready for production. Thus the new F.F.D. project and Diamond H will have a high technical and production synergy.

Finally we come to "market knowledge and marketing proficiency". Here Diamond H with its knowledge of marketing in the differently organized electric cooker industry would be at some disadvantage, however again by the time the new product could go into production, Diamond H would have gained proficiency by selling Harper Wyman products to the gas industry. Before money can be committed to the new product "market knowledge" must be gained to assess the likely market for the new F.F.D.. "Market knowledge" covers many things, but two will have a great bearing on the likelihood of new product success:-

1) The size of the market, or market segments which the new product is suitable for when sold at a profit.
2) The likely rate of acceptance of the new product by the market.

These two parameters will now be considered in detail.

12.2 Market Potential of the New F.F.D.

Baker (73) suggests that before a new product reaches the market place, the innovator should have undertaken a thorough demand analysis and must have:-

a) Identified potential users of the innovation.

b) Projected minimum/maximum levels of usage under various circumstances.

c) Selected the market segment with the greatest incentive to adopt the innovation as the target for his initial marketing efforts.

Fig. 63 shows the size and trends in various gas appliance market segments in the United Kingdom. Clearly, since the new F.F.D. is designed to replace the mercury F.F.D., the segment with the greatest incentive to adopt the innovation will be that into which the mercury device is now sold, i.e. the gas cooker segment. Fig. 63 reveals that this segment has stabilized at about 600,000 units per annum and it is hoped that if the new F.F.D. lives up to its promise then this will be the minimum market size.

Possibly the new product may be marketed in other segments. Except for very small boilers, the device would not be suitable for the central heating segment, (unless developed into a flame switch) and the same applies to the instant water heating segment. The space heater segment is very large indeed and consists mainly of wall mounted radiant gas fires. The new F.F.D. as envisaged at present would not have sufficient flow capacity for the larger fires, but if high flow versions were developed, then this device would be suitable for the whole segment. At the present time radiant fires are not fitted with F.F.D.'s, but with improving safety standards, this could well be a thing of the future. In fact in offering a simple, automatic, mercury-free F.F.D. system, the new device could precipitate the fitting of F.F.D.'s in this segment. To summarize, the likely market in the United Kingdom would certainly be up to 600,000 units per annum, with possibly another 900,000 units per annum if the market developed fortuitously.

Initially, U.K. marketing will be of prime interest, but later the possibility of developing export markets should be considered. Here the possibilites are enormous, and for instance the size of the United States mercury F.F.D. market has been estimated at 2,000,000 units per annum. (74). In Europe, as has been explained earlier, there is at present no mercury F.F.D. market and here the new device might be expected to develop the market share that the mercury F.F.D. now enjoys in the U.K. and U.S.A..

12.3 Market Acceptance of the New F.F.D.

Rogers (75) has proposed that the following innovation characteristics will have an affect on the rate of adoption of that innovation by the market.

a) Relative advantage
b) Communicability
c) Compatibility
d) Complexity
e) Divisibility

Although Rogers was primarily considering the rate of adoption by the market, clearly the product attributes listed above also determine its success. A product with a low scoring on Roger's criteria would be taken up so slowly by the market, that only a low market share would be achieved by the time the decline part of the life cycle were reached. Thus the above product attributes are crucial in deciding the success of a new product.

The market itself will have an affect on the acceptance of the new product and for instance such factors as the buyer behaviour and resistance to change found in the market place are important. However, because the resistance to the new product will vary from company to company, the marketing organization can seek out the "innovators" and "early adopters" (73) and make them the target of early marketing effort, which if successful will bring about the first sales of the product. Later the strategy can be adjusted to try to modify the opinion of the "early majority", "late majority" and "laggards" to the new product and thus increase sales. The point here is that to some degree the market reaction to the device can be taken cognisance of and manipulated by the marketing organization. On the other hand in the case being studied here, the new product's attributes are diffucult to change, being determined by the limited variability of the new F.F.D. for technological reasons and the state of the market as it exists at present. Because they are so fundamental, the new F.F.D.'s characteristics will now be studied in detail.

12.3.1 Relative Advantage

Baker (73) describes relative advantage as the "benefit conferred on, or available to the adopter of an innovation, adjusted to take cognisance of the adopter's present 'economic status'".

The mercury F.F.D. has been used for many years in gas cookers and in the main has proved both safe and reliable, thus the relative advantage for the cooker O.E.M.'s in changing to the new F.F.D. are not high. The end user of the cooker, usually a home owner, is more interested in the functionality, reliability and appearance of the cooker, rather than such details as the type of F.F.D. fitted, although if it became widely known that the F.F.D. contained mercury, more than a few users would probably become worried. Therefore there has been little pressure for change either from the O.E.M.'s or the end users and in fact the motivation for change has come entirely from the British Gas Corporation. British Gas were extremely worried about possible toxic effects caused by mercury leakage and the possibility of adverse publicity for gas cookers, so they have been encouraging the F.F.D.

manufacturers to improve their products and develop a new mercury-free F.F.D.. Moral pressure from British Gas on the cooker manufacturers would certainly help increase the "relative advantage" of fitting the new F.F.D.. If British Gas were to take the ultimate step of banning the mercury F.F.D. then the "relative advantage" of the new F.F.D. would become enormous, since it would be the only device which would simply substitute for the mercury device.

In export markets currently using the mercury F.F.D. (e.g. U.S.A. and Canada) the relative advantage of the new device would be dependent upon the strength of worries about mercury. In markets not using the mercury F.F.D. the "relative advantage" would be large since for the first time they would be able to enjoy the benefits of the mercury device (simple, automatic, no electricity supply needed) without the mercury.

12.3.2 Communicability

This is the degree to which the benefits of using the new innovation are observable and desirable to others. The greater this factor is the more rapidly the innovation will diffuse into the market place. For a simple component such as the new F.F.D., the communicability should be high.

12.3.3 Compatibility

Compatibility is the "degree to which an innovation is consistent with the existing values and past experiences of the adopters" (73). Thus for markets conditioned to using the mercury F.F.D., this is very high indeed, and this factor should aid rapid diffusion of the new F.F.D.. In markets where mercury F.F.D.'s have not been used this would be a barrier to acceptance.

12.3.4 Complexity

This is the degree to which the new innovation is difficult to understand or use. Clearly for this device complexity will prevent no barriers to its diffusion.

12.3.5 Divisibility

This is the extent to which an innovation can be tried on a limited basis. With this device, cheap small scale trials are no problem and this should be a great aid to diffusion.

The following chart summarizes the new F.F.D.'s characteristics in markets where mercury F.F.D.s have been used, and where they have not.

NEW F.F.D. CHARACTERISTICS AS AN ADOPTION DETERMINANT

+ = Characteristic aids diffusion
N = Characteristic does not affect diffusion
– = Characteristic retards diffusion

CHARACTERISTIC	MARKETS USING MERCURY FFD	MARKETS NOT USING MERCURY FFD
Relative Advantage	N (+ if mercury prohibited)	+
Communicability	+	+
Compatibility	+	–
Complexity	+	+
Divisibility	+	+

Thus assuming that the new F.F.D. lives up to its promise as a substitute for the mercury F.F.D., then the barriers to its diffusion into the market place do not seem very high.

12.4 The Future

Responsibility for the new F.F.D. has now passed to Diamond H Controls Ltd., although the products are still to be marketed under the Harper Wyman name to help ensure continuity. Diamond H is a large and successful company which has a good track record in the development and marketing of new electric controls. This augurs well for the new F.F.D. as Harper Wyman, with its very limited new product development capability would have had much difficulty in developing this device to the point where it satisfied British Gas and was ready to be mass produced.

As has previously been noted, Diamond H has little experience marketing in the gas industry. However this is changing and at the time of writing the company has been producing gas thermostats and F.F.D.s for some six months and is rapidly gaining experience. Indeed, it now appears that customers whom Harper Wyman had lost are showing renewed interest in the products as produced by Diamond H. In part this may be due to the fact that Diamond H is a much larger organization with more resources, which projects a better image into the market place, instilling more confidence into the customers. Customer confidence in industrial marketing is of paramount importance, as the customer depends heavily upon his suppliers. In this way Diamond H is able to compete in the market on an equal basis with Teddington and Concentric, which are both large organisations.

The new F.F.D. is at present being developed for production and by the time it is ready for sale it is anticipated that Diamond H will be well ensconced in the market, with a higher market share than was previously enjoyed by Harper Wyman. By this time also, the company will have become fully experienced in gas control marketing. Therefore it is the opinion of the author that the new F.F.D. will have a much greater chance of success with Diamond H than it would have enjoyed with Harper Wyman.

Applications for U.K. and foreign patents have been submitted by the inventors (Harrison, Reiter and Diprose) and Bath University for the gas filled F.F.D.. It is intended that Diamond H be given exclusive rights to exploit the patents and levy royalties. If the applications result in strong patents, then this could add flexibility to the Diamond H marketing policy. For instance in foreign markets where the company had little marketing expertise, Diamond H could license a local manufacturer to make the device on payment of royalties. In the U.K., where customers usually multi-source, it could well be prudent to license other U.K. manufacturers to make the device.

CHAPTER 13

CONCLUSION

13.1 Engineering Conclusions

It has been demonstrated that the gas filled F.F.D. can be made with a sufficiently good performance to substitute for the mercury F.F.D.. Tests completed on prototypes have shown that the gas filled F.F.D. should certainly have sufficient reliability to be used in a cooker oven. Without the effects of mercury leaching the phial walls, the life of a well-made gas filled F.F.D. should greatly exceed that of the mercury F.F.D.. The speed of operation of the prototypes was well within that specified by BS 5258 (table 5) and there is no fundamental reason why all of the requirements of BS 6047 part 1 should not be met. In section 5.1, which looked at the features needed by an alternative to the mercury F.F.D., the following requirements were suggested:-

a) It must be cheap to make
b) It must be self contained and not need an electricity supply
c) It must open and shut automatically
d) It must have a flexible connection between the sensor and valve

It will be seen that the gas filled F.F.D. meets requirements b, c and d and, as it contains almost the same components as the mercury F.F.D., any cost differences between the two devices will be minimal. In fact the new F.F.D. is so like the mercury F.F.D., it is almost a direct replacement for it, the only difference being the larger phial which may necessitate a larger fixing bracket.

In section 5.1 further requirements were suggested, which would make the F.F.D. suitable for appliances other than cookers:-

e) It must be able to sense standing pilots without premature breakdown

f) It must have a high cycle life

g) It should have a high gas flow capability, if possible up to 3 cubic metres per hour at 0.75 mb pressure differential

h) It should have a faster response time than that of bimetallic, thermoelectric or mercury devices.

The long life requirements e and f could be met by using a thermal system with a thick walled phial (say 1 mm or 2 mm thick). Such a thermal system could then be used in boilers, sensing a standing pilot (requirement e), or the cycling main burner flame (requirement f), depending upon which was most suitable for the application in question. This development of the gas filled F.F.D. might well exceed the life of the thermoelectric F.F.D. (which is not very long) and bring the advantages of the totally automatic F.F.D. to boilers.

Requirement g is necessary to cope with the high gas inputs needed by most other appliances. The experimental prototypes built used the standard 25 mm diameter valve plate, designed for use with the high stroke mercury thermal system. This could be developed to give higher flows by increasing the valve plate diameter, or going to a "double beat" valve, or using levers to magnify the capsule movement. Even so it is doubtful if this type of F.F.D. could ever meet the flow requirement of a large boiler. However, as boilers mainly have electric control systems (with solenoid valves to control the gas), the development of a gas filled "flame switch" should be attempted. Diamond H Controls Ltd., with its electric control experience, should be very well equipped to make this development, which would be well worth while, as the central heating boiler market is approximately 500,000 units per annum (fig. 63). In fact, as the use of electronic control systems is likely to increase in the future, the market growth for a flame switch could well be large.

The speed of response of the gas filled F.F.D. is similar to that of the mercury F.F.D., but this is sufficiently good for most domestic appliance purposes. It is suggested that the gas filled F.F.D., being much less inclined to block in the manner of the mercury F.F.D., would be unlikely to become slow in operation with use, or fail in the open position.

13.2 Marketing Conclusions

The marketing analysis revealed the considerable power that British Gas had in the market channel and that this power is likely to continue despite, as now seems likely, its being divested of its retail outlets. Given that British Gas originally voiced the worries about the mercury F.F.D., it is assumed that this power will be to the advantage of the new device. In section 12.2 the substantial size of the possible market was pointed out, especially if the F.F.D. was developed to be suitable for other appliances. The analysis of the likely market acceptance of the device (section 12.3) showed there to be no significant barriers for the new F.F.D. to overcome, either in U.K. markets, or export markets. The possibility of exporting this F.F.D. to markets where the mercury F.F.D. has not been acceptable should be explored, as for the first time a totally automatic F.F.D. is available without the disadvantage of mercury.

At the time of writing, (August 1981), production prototypes are being prepared by Diamond H Controls Ltd., and when ready, these will be submitted to British Gas for approval. In conclusion, it is considered that there is no reason why, given competent development, production and enthusiastic marketing, the gas filled F.F.D. should not succeed in the market place.

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APPENDIX 1

PROGRAM ffd.basic

Appendix 1

```
00100 '                    PROGRAM FFD.BASIC
00110 '-----------------------------------------------------------------------
00120 '  CALCULATES CAPSULE EXTENSION AT DIFFERENT PHIAL TEMPERATURES
00130 '  CAPSULE PRESSURE EXTENSION DATA TAKEN FROM SPECIFIED FILE
00140 '  PERFORMANCE DATA PUT IN FILE "output"
00150 '  PERFORMANCE DATA ALSO PUT IN FILE "file31"
00160 '
00170 '-----------------------------------------------------------------------
00180 '
00190 file #2:"output"
00200 file #3: "file31"
00210 scratch #2
00220 scratch #3
00230 print #2: "DATE OF COMPUTATION       ",dat$
00240 print "TYPE NAME OF PRESSURE-EXTENSION DATA FILE"
00250 input z1$
00260 file #1: z1$
00270 print "INPUT  PHIAL VOL (mm^3), CAPSULE RAD (mm), FILL PRESSURE (KPa ABS), DEAD VOL. (mm^3),
 START PRESSURE (KPa) "
00280 input v,r,p,u,o
00290 p=p-101.325
00300 s=0.5
00310 print #2: " "
00320 print #2: " "
00330 print #2: "PHIAL VOLUME mm^3            =",v
00340 print #2: "CAPSULE RADIUS mm            =",r
00350 print #2: "FILL PRESSURE KPa GAUGE      =",p
00360 print #2: "DEAD VOLUME mm^3             =",u
00370 print #2: "START PRESSURE KPa           =",o
00380 print #2: " "
00390 print #2: " "
00400 dim h (40,2)
00410 mat h=zer
00420 i=1
00430 if end #1 goto 520
```

```
00440 input #1: p1,e1
00450 h(i,1)=p1
00460 h(i,2)=e1
00470 i=i+1
00480 if i=40 goto 500
00490 goto 430
00500 print "TOO MUCH DATA IN FILE"
00510 goto 1110
00520 p1=0
00530 e1=0
00540 for j=1 to 40
00550 p2=h(j,1)
00560 e2=h(j,2)
00570 if p<=0 goto 610
00580 if p2<p1 goto 670
00590 if p>p2 goto 640
00600 if p<=p2 goto 690
00610 y=0
00620 p=p+101.325
00630 goto 730
00640 p1=p2
00650 e1=e2
00660 next j
00670 print "NOT ENOUGH DATA"
00680 goto 1110
00690 y=e1+(p-p1)*(e2-e1)/(p2-p1)
00700 e=y*r*r*s*3.1416+u+v
00710 p=(p+101.325)*e/(v+u)
00720 p3=int(p*10^3+0.5)/10^3
00730 print #2: "NOMINAL FILL PRESSURE KPa  =",p3
00740 print #2: " "
00750 print #2: " "
00760 print "TEMP DEG C","STROKE","TOTAL EXTENSION"
00770 print #2:"TEMP DEG C","STROKE","TOTAL EXTENSION"
00780 b=0
```

```
00790 t=300
00800 gosub 1200
00810 if z=w goto 970
00820 if z>w goto 850
00830 b=b+0.1
00840 goto 800
00850 b=b-0.01
00860 if b<0 goto 910
00870 gosub 1200
00880 if z<w goto 920
00890 if z=w goto 970
00900 if z>w goto 850
00910 b=0
00920 b=b+0.001
00930 gosub 1200
00940 if z<w goto 920
00950 if z=w goto 970
00960 if z>w goto 970
00970 b=int(b*10^3+0.5)/10^3
00980 t1=t-273
00990 g=b-y
01000 g=int(g*10^3+0.5)/10^3
01010 print t1,g,b
01020 print #2:t1,g,b
01030  print #3:using"-######,-##.####",t1,g
01040 if t<301 goto 1070
01050 t=t+50
01060 goto 1080
01070 t=323
01080 if t>1100 goto 1110
01090 b=0
01100 goto 800
01110 print "ANY MORE DATA? -ANSWER y OR n "
01120 input z2$
01130 reset
```

```
01140 if z2$="y" goto 240
01150 stop
01160 '
01170 '
01180 '
01190 '
01200 rem pressure calc subroutine follows
01210 d=b*r*r*s*3.1416
01220 a=t*300*(v+u+d)
01230 c=v*300+t*(u+d)
01240 f=a/c
01250 m=p*(v+u)*f/(300*(v+u+d))
01260 w=m-o-101.325
01270 p1=0
01280 e1=0
01290 for j=1 to 40
01300 p2=h(j,1)
01310 e2=h(j,2)
01320 if e2<e1 goto 1410
01330 if b>e2 goto 1360
01340 if e2=0 goto1360
01350 if b<=e2 goto 1390
01360 e1=e2
01370 p1=p2
01380 next j
01390 z=p1+(b-e1)*(p2-p1)/(e2-e1)
01400 return
01410 print "NO MORE DATA FOR SUBROUTINE"
01420 goto 1110
01430 end
```

APPENDIX 2

FILE output

The data shown is for thermal system number 31.

Appendix 2

DATE OF COMPUTATION 07/21/81

PHIAL VOLUME mm^3	=	500
CAPSULE RADIUS mm	=	9
FILL PRESSURE KPa GAUGE	=	164.675
DEAD VOLUME mm^3	=	60
START PRESSURE KPa	=	0

NOMINAL FILL PRESSURE KPa = 288.88

TEMP DEG C	STROKE	TOTAL EXTENSION
27	0	0.379
50	0.037	0.416
100	0.11	0.489
150	0.173	0.552
200	0.228	0.607
250	0.277	0.656
300	0.316	0.695
350	0.352	0.731
400	0.384	0.763
450	0.413	0.792
500	0.437	0.816
550	0.458	0.837
600	0.477	0.856
650	0.495	0.874
700	0.512	0.891
750	0.527	0.906
800	0.541	0.92

<u>APPENDIX 3</u>

PROGRAM var.basic

Appendix 3

```
00100 '
00110 '                          PROGRAM VAR.BASIC
00120 '-----------------------------------------------------------------------
00130 '     COMPUTES VARIATION OF CAPSULE EXTENSION WITH AMBIENT TEMPERATURE
00140 '     COMPUTES VARIATION OF Ts WITH AT. PRESS. AND AMB. TEMP.
00150 '     CAPSULE PRESSURE EXTENSION DATA TAKEN FROM SPECIFIED FILE
00160 '     RESULTS PUT IN FILE "voutput"
00170 '     RESULTS ALSO PUT IN "file32"
00180 '
00190 '-----------------------------------------------------------------------
00200 '
00210 print "TYPE NAME OF PRESSURE-EXTENSION DATA FILE ",
00220 input a1$
00230 file #1: a1$
00240 print "INPUT V(mm^3),R(mm),Pf(KPa ABS),U(mm^3),O(KPa),Ts(DEG C) "
00250 input v,r,p,u,o,t
00260 t=t+273
00270 p=p-101.325
00280 s=0.5
00290 print "Te deg C","TOTAL EXT."
00300 file #2: "voutput"
00310 scratch #2
00320 file #3: "file32"
00330 scratch #3
00340 print #2: "DATE OF COMPUTATION              ",dat$
00350 print #2: " "
00360 print #2: " "
00370 print #2: "PHIAL VOL mm^3                  =",v
00380 print #2: "CAPSULE RAD. mm                 =",r
00390 print #2: "FILL PRESSURE KPa GAUGE         =",p
00400 print #2: "DEAD VOLUME mm^3                =",u
00410 print #2: "START PRESSURE KPa              =",o
00420 print #2: "OPENING TEMP. (Ts), DEG C       =",t-273
00430 print #2: " "
00440 print #2: " "
```

```
00450 print #2: " "
00460 print #2:"Te deg C","TOTAL EXT."
00470 dim h (40,2)
00480 mat h=zer
00490 i=1
00500 if end #1 goto 590
00510 input #1: p1,e1
00520 h(i,1)=p1
00530 h(i,2)=e1
00540 i=i+1
00550 if i=40 goto 570
00560 goto 500
00570 print "TOO MUCH DATA IN FILE"
00580 goto 930
00590 p1=0
00600 e1=0
00610 for j=1 to 40
00620 p2=h(j,1)
00630 e2=h(j,2)
00640 if p2<p1 goto 700
00650 if p>p2 goto 670
00660 if p<=p2 goto 720
00670 p1=p2
00680 e1=e2
00690 next j
00700 print "NOT ENOUGH DATA"
00710 goto 930
00720 y=e1+(p-p1)*(e2-e1)/(p2-p1)
00730 e=y*r*r*s*3.1416+u+v
00740 p=(p+101.325)*e/(v+u)
00750 b=0
00760 t1=273
00770 gosub 1920
00780 t2=t1-273
00790 print t2,b
```

```
00800 print #2: t2,b
00810 if t2>=150 goto 930
00820 t1=t1+10
00830 if t2=0 goto 870
00840 if t2=80 goto 900
00850 b=0
00860 goto 770
00870 b1=b
00880 b=0
00890 goto 770
00900 b2=b
00910 b=0
00920 goto 770
00930 n1=(b2-b1)/80
00940 n2=(b-b2)/70
00950 n3=(b-b1)/150
00960 print " "
00970 print "db/dTe 0 to 80 deg C",n1
00980 print "db/dTe 80 to 150 deg C",n2
00990 print "db/dTe 0 to 150 deg C",n3
01000 print "INPUT TEMP COMPENSATION FACTOR"
01010 print #2: " "
01020 print #2: " "
01030 print #2: " "
01040 print #2: " "
01050 print #2: "db/dTe 0 to 80 deg C            =",n1
01060 print #2: "db/dTe 80 to 150 deg C          =",n2
01070 print #2: "db/dte 0 to 150 deg C           =",n3
01080 print #2: " "
01090 print #2: " "
01100 input n
01110 print #2: "TEMP CORRECTION FACTOR mm/deg C   =",n
01120 print #2: " "
01130 print #2: " "
01140 print #2: " "
```

```
01150 print #2: " "
01160 t1=300
01170 gosub 1920
01180 t=t+75
01190 t1=273
01200 dim c (8,9)
01210 mat c=zer
01220 for i=1 to 8
01230 for j=2 to 9
01240 b1=b+n*(t1-300)
01250 p1=0
01260 e1=0
01270 for k=1 to 40
01280 p2=h(k,1)
01290 e2=h(k,2)
01300 if e2<e1 goto 1390
01310 if b1>e2 goto 1340
01320 if e2=0 goto 1340
01330 if b1<=e2 goto1370
01340 e1=e2
01350 p1=p2
01360 next k
01370 z=p1+(b1-e1)*(p2-p1)/(e2-e1)
01380 goto 1410
01390 print "NOT ENOUGH PRESSURE-EXTENSION DATA"
01400 stop
01410 z1=(p*t*t1*(v+u))/(300*(v*t1+t*(u+b1*r*r*s*3.1416)))
01420 z2=z1-z-101.325
01430 print #3 : using "-#####  -#####.####",t1-273,z2
01440 t1=t1+20
01450 c(i,j)=z2
01460 next j
01470 c(i,1)=t-273
01480 t1=273
01490 t=t-25
```

```
01500 next i
01510 print "  Ts        Te=0, Te=20, Te=40, Te=60, Te=80,Te=100,Te=120,Te=140"
01520 print" "
01530 mat print using "-###.#,    -###.#,-###.#,-###.#,-###.#,-###.#,-###.#,-###.#,-###.#",c
01540 print #2: " "
01550 print #2: " "
01560 print #2: " "
01570 print #2: "  Ts        Te=0, Te=20, Te=40, Te=60, Te=80,Te=100,Te=120,Te=140"
01580 print #2: " "
01590 mat print #2 : using "-###.#,    -###.#,-###.#,-###.#,-###.#,-###.#,-###.#,-###.#,-###.#",c
01600 stop
01610 '
01620 '
01630 '
01640 '
01650 rem PRESSURE CALC. SURROUTINE FOLLOWS
01660 d=b*r*r*s*3.1416
01670 a=t*t1*(v+u+d)
01680 c=v*t1+t*(u+d)
01690 f=a/c
01700 m=p*(v+u)*f/(300*(v+u+d))
01710 w=m-o-101.325
01720 p1=0
01730 e1=0
01740 for j=1 to 40
01750 p2=h(j,1)
01760 e2=h(j,2)
01770 if e2<e1 goto 1860
01780 if b>e2 goto 1810
01790 if e2=0 goto1810
01800 if b<=e2 goto 1840
01810 e1=e2
01820 p1=p2
01830 next j
01840 z=p1+(b-e1)*(p2-p1)/(e2-e1)
```

```
01850 return
01860 print "NO MORE DATA FOR SUBROUTINE"
01870 goto 930
01880 '
01890 '
01900 '
01910 '
01920 rem PRESSURE COMPARISON SUBROUTINE FOLLOWS
01930 gosub 1650
01940 if z=w goto 2100
01950 if z>w goto 1980
01960 b=b+0.1
01970 goto 1930
01980 b=b-0.01
01990 if b<0 goto 2040
02000 gosub 1650
02010 if z<w goto 2050
02020 if z=w goto 2100
02030 if z>w goto 1980
02040 b=0
02050 b=b+0.001
02060 gosub 1650
02070 if z<w goto 2050
02080 if z=w goto 2100
02090 if z>w goto 2100
02100 b=int(b*10^3+0.5)/10^3
02110 return
02120 end
```

APPENDIX 4

FILE voutput

The data shown is for experimental F.F.D. number 31.

Appendix 4

DATE OF COMPUTATION 07/23/81

PHIAL VOL mm^3	=	500
CAPSULE RAD. mm	=	9
FILL PRESSURE KPa GAUGE	=	164.675
DEAD VOLUME mm^3	=	60
START PRESSURE KPa	=	0
OPENING TEMP. (Ts), DEG C	=	325

Te deg C	TOTAL EXT.
0	0.689
10	0.699
20	0.707
30	0.716
40	0.724
50	0.732
60	0.74
70	0.747
80	0.754
90	0.761
100	0.768
110	0.774
120	0.781
130	0.787
140	0.793
150	0.798

dh/dTe 0 to 80 deg C	=	8.125 E-4
dh/dTe 80 to 150 deg C	=	6.28571 E-4

Appendix 4

db/dte 0 to 150 deg C = 7.26667 E-4

TEMP CORRECTION FACTOR mm/deg C = 0.0007

Ts	Te=0,	Te=20,	Te=40,	Te=60,	Te=80,	Te=100,	Te=120,	Te=140
400.0,	25.2,	29.0,	31.9,	34.0,	35.4,	36.2,	36.5,	36.3
375.0,	16.1,	19.4,	21.9,	23.6,	24.7,	25.1,	25.1,	24.5
350.0,	6.7,	9.5,	11.6,	12.9,	13.6,	13.7,	13.3,	12.5
325.0,	-3.1,	-0.7,	1.0,	1.9,	2.2,	1.9,	1.2,	0.1
300.0,	-13.2,	-11.2,	-10.0,	-9.5,	-9.6,	-10.2,	-11.2,	-12.7
275.0,	-23.6,	-22.1,	-21.3,	-21.2,	-21.7,	-22.6,	-24.0,	-25.7
250.0,	-34.4,	-33.3,	-33.0,	-33.3,	-34.1,	-35.4,	-37.1,	-39.1
225.0,	-45.5,	-44.9,	-45.1,	-45.7,	-46.9,	-48.6,	-50.6,	-53.0

Table 1

Flame Detection Methods Needing Electricity Supply

TYPE	INPUT TO SENSOR	COMMENTS	REFERENCES
Flame Conductivity	Electrical conductivity of flame	Electrical leakage on insulators can simulate a flame	1, 2, 4, 8, 9, 10
Flame Rectification	Flame directional conductivity	Detection of rectification effect eliminates problems due to electrical leakage	8, 9, 10, 11
Flame Voltage	Voltage generated by flame (can be up to 2 volts)	Very low current output necessitates high imput impedance detector	8
Infra Red	Infra red radiation from flame	Can be affected by background radiation from hot surroundings. This can be overcome by making the detector system responsive to radiation with a flicker superimposed on it.	8, 10, 11
Ultra Violet	U.V. light from flame	Detector must be kept cool and shielded from sunlight and other sources of U.V. such as spark igniters	8, 10, 11

Table 1 (continued)

TYPE	INPUT TO SENSOR	COMMENTS	REFERENCES
Inverted Flame	Visible light from flame	Stream of gas injected into blue flame to increase visible light output. Light detected by a photo conductor	8
Partial Reflection	Light reflected from flame	Light beam strikes flame. Photocell picks up reflected light	8
Thermistor	Flame heat	Thermistors not available for high temperatures (300 °C max)	8
Salt Cell	Flame heat	When salt melts its electrical resistance drops. This could possibly control a magnetic valve without the need for an amplifier	8
Thermocouple Switch	Flame heat	Thermocouple current operates electromagnetic switch	10
Mercury Flame Switch	Flame heat	Thermal element similar to mercury F.F.D. operates a microswitch	15

Table 2

FLAME DETECTION METHODS PRODUCING MECHANICAL MOTION

TYPE	OUTPUT FROM SENSOR	DISADVANTAGES	REFERENCES
Mercury	Mechanical Motion	a) Possible mercury vapour hazard b) Hot mercury dissolves metal walls of device redepositing it elsewhere causing blockage	2, 4, 16
Thermoelectric	Electric current. Sufficient current to operate electromagnet which can hold spring loaded valve open	a) Insufficient energy to open valve. This must be done manually b) Thermocouple life quite short	1, 2, 3, 4, 9, 10
Bimetallic Strip	Mechanical Motion	a) Bimetallic sensor can warp after long use, holding valve open b) Valve must be connected by inflexible mechanical linkage to sensor c) Exposed mechanism means that it is not tamperproof	1, 2, 4, 9
Bimetallic Rod and Tube	Mechanical Motion	a) Small movements generated	1, 2

Table 2 (continued)

TYPE	OUTPUT FROM SENSOR	DISADVANTAGES	REFERENCES
Unimetallic	Mechanical Motion	a) Very small movements available b) Inflexible linkage between sensor and valve	2, 9
Porous Plug	Pressure drop across plug. This could be used to operate a relay valve.	a) Expensive due to need for complex relay valve b) Pressure changes developed small 6.75 mb on prototype. c) Blockage of porous plug could simulate a flame condition.	8
Curie Temperature	Mechanical Motion	a) Difficult to construct. b) Forces generated quite low.	8

Table 3

MERCURY F.F.D. FIELD FAILURE DATA

FAILURE MODE	FIELD FAILURES IN 10 YEAR LIFE
Swarf causing valve leakage	0.7%
Capsule cracking	2.1%
Capsule-boss weld cracking	0.3%
Capsule permanent set	2.1%
Capillary	0.4%
Blockage	4.0%
Phial cracking	5.0%
Phial closure weld failure	0.4%
TOTAL	15.0%

NOTES

1) U.K. population of mercury F.F.D.'s
2,156,000 in December 1977

2) Yearly replacement rate = 1.5% (approximately 32,000)

3) Taken from (28)

Table 4

FAILURES EXPERIENCED IN CYCLIC TESTING OF MERCURY VAPOUR FLAME FAILURE DEVICES

TYPE	NUMBER TESTED	NO. OF FAILURES	NO. OF CYCLES AT FAILURE	TYPE OF FAILURE	CAUSE OF FAILURE
			0	(	(
			0	(	(Swarf on valve pad
			0	(	(
			0	(	(
			0	(Leaking (unsafe)	(
			2020	(	(
			2040	(	Bellows rupture
Mercury Vapour	230	19	4040	(	Bellows rupture
			5500	(	Swarf on valve pad
			6000	Closed (safe)	Bellows rupture
			6000	Closed (safe)	" "
			6075	Leaking (unsafe)	" "
			6315	Closed (safe)	" "
			6390	Leaking (unsafe)	" "
			6800	Closed (safe)	" "
			7300	" "	" "
			7600	" "	" "
			7680	Leaking (unsafe)	" "
			8750	Closed (safe)	" "

Taken from Wharf (29)

Table 5

SUMMARY OF BS 5258 F.F.D. REQUIREMENTS

BS 5258 PART NUMBER	APPLIANCE	F.F.D. REQUIRED?	MAX. OPENING TIME	MAX. CLOSING TIME
1	Boiler	yes	40 seconds	60 seconds
	Circulator	yes	90 seconds	90 seconds
2	Cookers	yes	90 seconds	90 seconds
3	Drying Cabinet	yes (except when flames can be seen with doors closed)	90 seconds	90 seconds
4	Ducted air heaters	yes	40 seconds	60 seconds
5	Gas fires	Only when gas supply to main burner is turned on automatically	90 seconds	3 minutes

Table 5 (continued)

BS 5258 PART NUMBER	APPLIANCE	F.F.D. REQUIRED?	MAX. OPENING TIME	MAX. CLOSING TIME
6	Refrigerators and food freezers	Only when 3rd family gas is used	90 seconds	90 seconds
7	Storage water heater	yes	<8 kw heat input	
			90 seconds	90 seconds
			>8 kw heat input	
			40 seconds	60 seconds
8	Combined appliances	Necessary in boiler	Boiler	
			40 seconds	60 seconds
	Gas fire/ back boiler	Only necessary on gas fire if turned on automatically	Circulator	
			90 seconds	90 seconds
			Gas fire	
			90 seconds	3 minutes

Table 5 (continued)

BS 5258 PART NUMBER	APPLIANCE	F.F.D. REQUIRED?	MAX. OPENING TIME	MAX. CLOSING TIME
10	Non catalytic flueless space heater	yes	90 seconds	90 seconds
11	Catalytic flueless space heater	Not applicable	----	----
12	Decorative log fires	Only necessary if turned on automatically, or if greater than 7.3 kw heat input	90 seconds	2 minutes

DIFFUSION CONSTANTS

TEMP. ^{o}C	MATERIAL COMBINATION	D cm^2/sec	REF
1100 (800)	O^{2-} in Cr_2O_3	10^{-15} (10^{-19})	56
1100	Cr^{3+} in Cr_2O_3	10^{-11}	57
800	Oxygen in Fe $(\alpha+\delta)$	8.3×10^{-7}	52
800	Nitrogen in Fe $(\alpha+\delta)$	1.36×10^{-6}	52
1100	Nitrogen in Fe (γ)	4.7×10^{-7}	52

Table 7

COMPARISON OF DIAPHRAGM MATERIALS

MATERIALS	2% YIELD STRESS (σ_y) MPa	ELASTIC MODULUS (E) GPa	RATIO $\sigma_y/E \times 10^3$
Beryllium-copper*	1066	127.5	8.4
Monel K-500*	600	165	3.6
Phosphor bronze ½H	386	107	3.6
H	579		5.4
Inconel X 750*	900	221	4.1
17-7 PH*	1275	195	6.5
¼H	520	200	2.6
302 ½H	800	200	4
H	1100	200	5.5

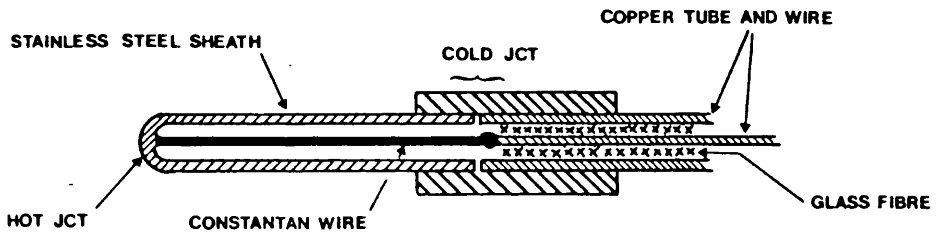
* Indicates precipitation hardening.

PROPERTIES OF FUEL GASES

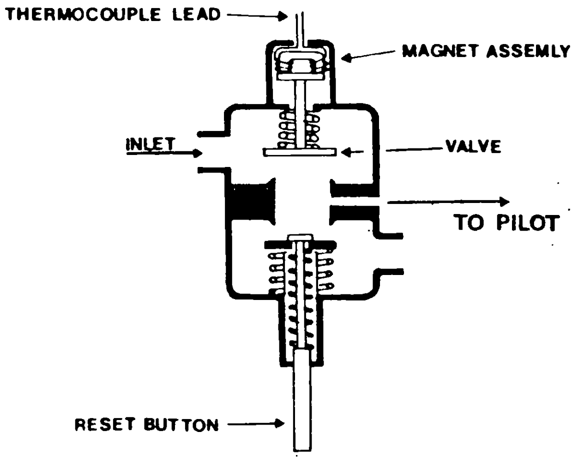
FUEL GAS	RELATIVE DENSITY	WOBBE INDEX (S.I.)
Normal U.K. town Gas	0.47	27.2
U.K. natural gas	0.586	50.7
Propane	1.552	75.4
Butane	2.006	85.9
Nitrogen*	0.967	----

* Included for flow measurement purposes.

Figure 1



THERMOCOUPLE



VALVE

Schematic diagram of a thermoelectric flame failure device.

Figure 2

A typical thermoelectric flame failure device.

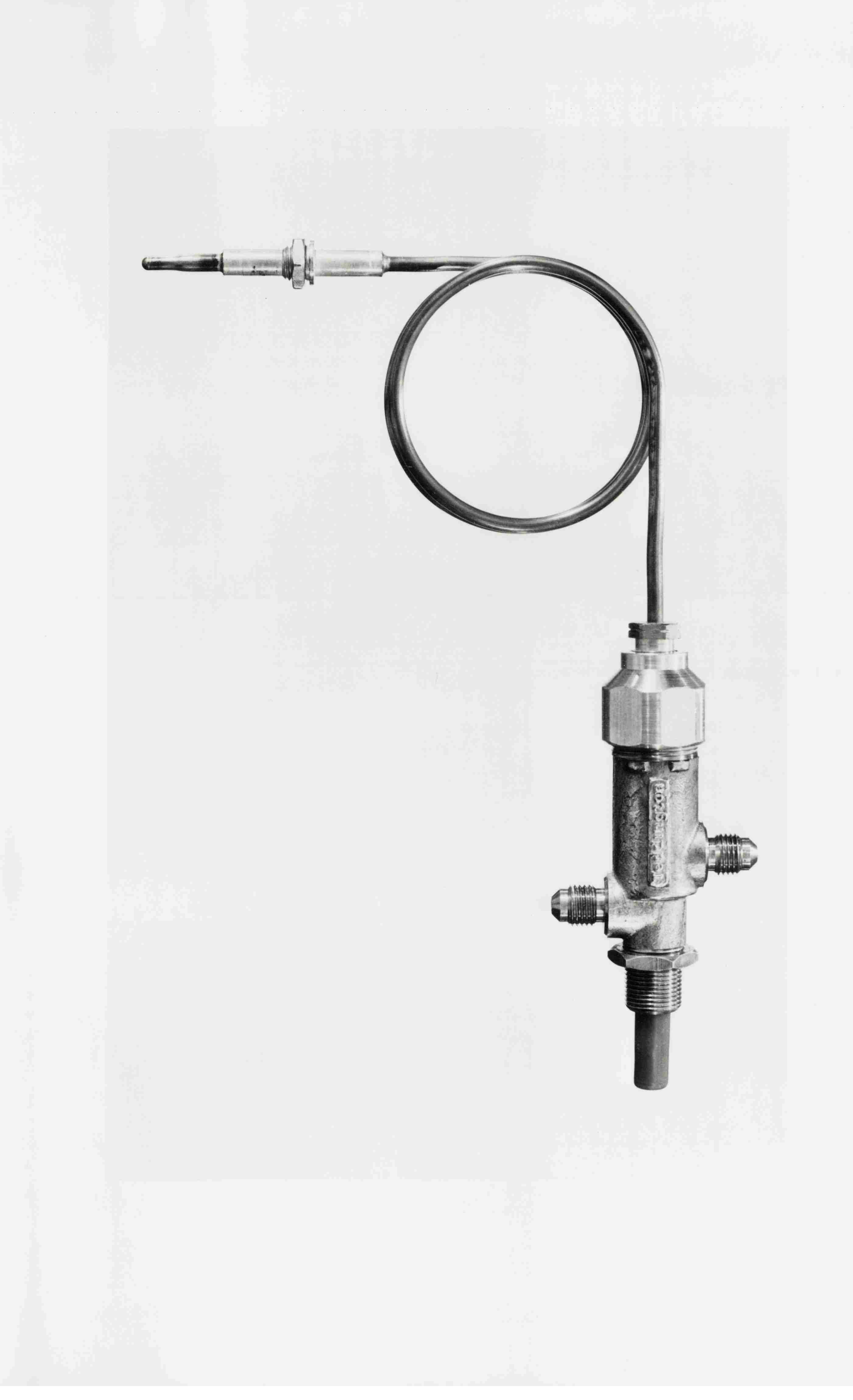
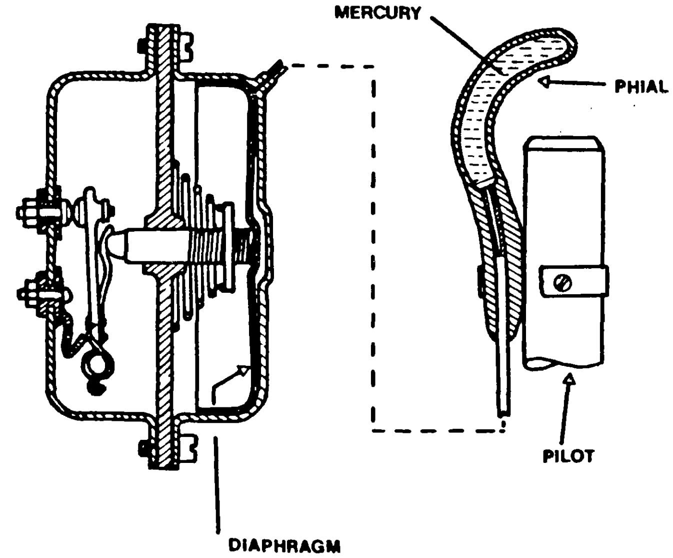
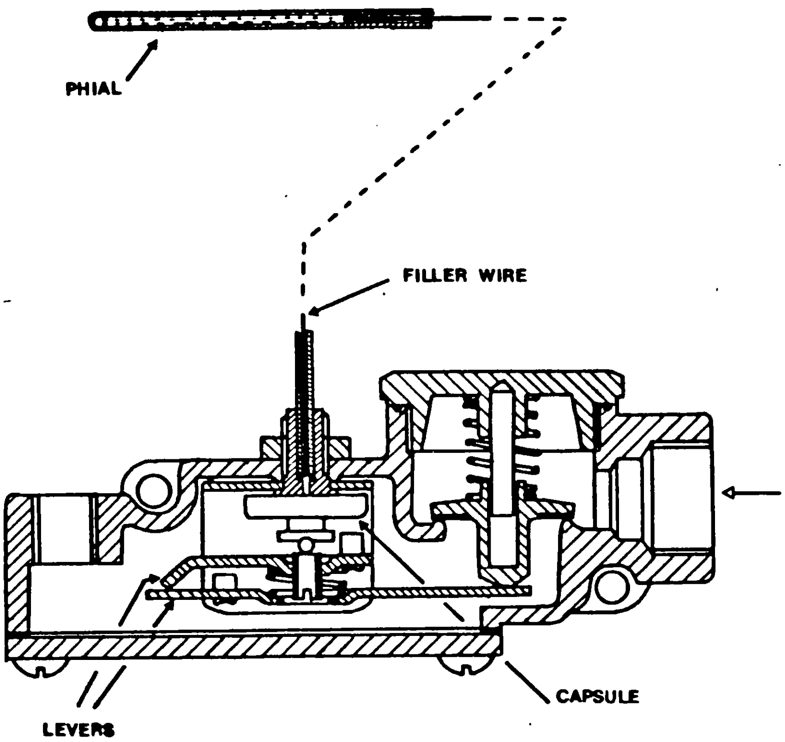


Figure 3



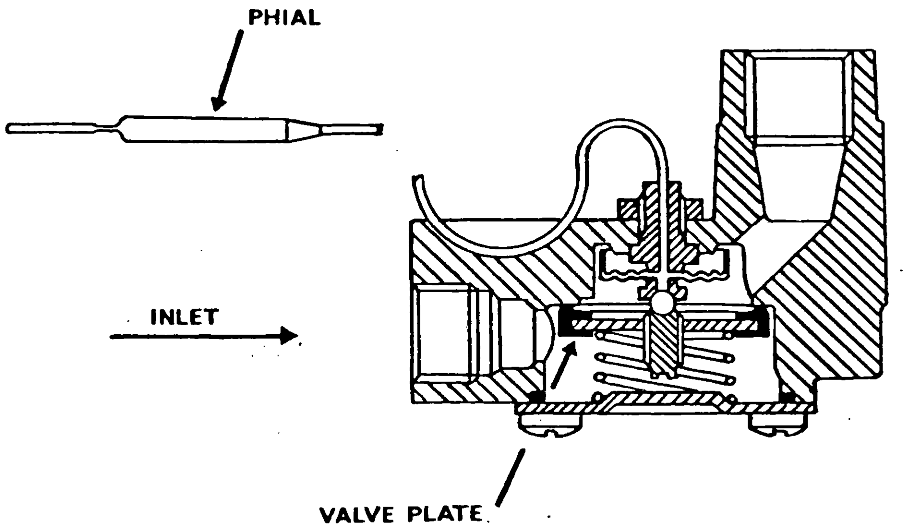
Cobb flame switch.
Taken from U.S. patent 2640313 (15).

Figure 4



Weber flame failure device.
Taken from U.S. patent 3213922 (16).

Figure 5



Harper Wyman 5920 mercury flame failure device.

Figure 6

A Harper Wyman type 5920 mercury flame failure device.

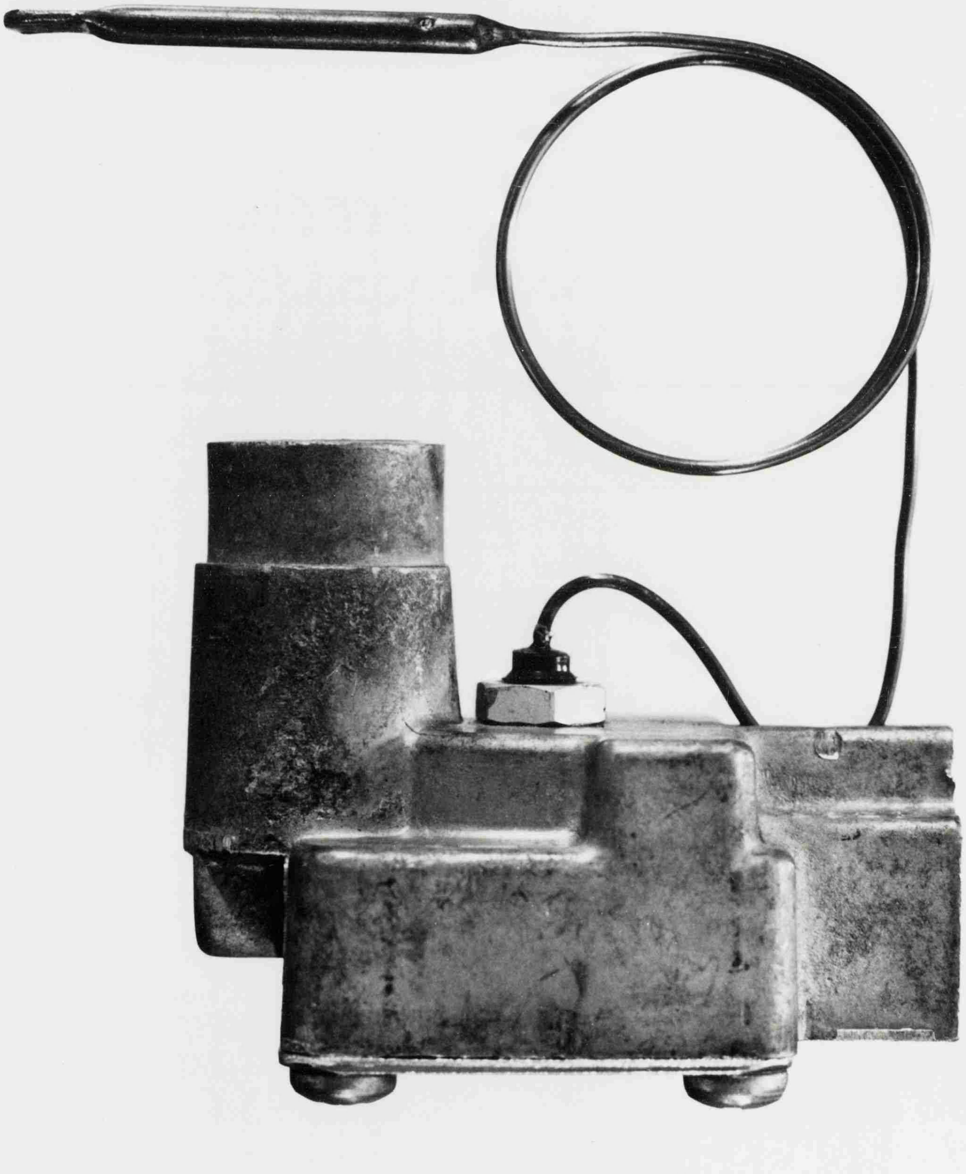
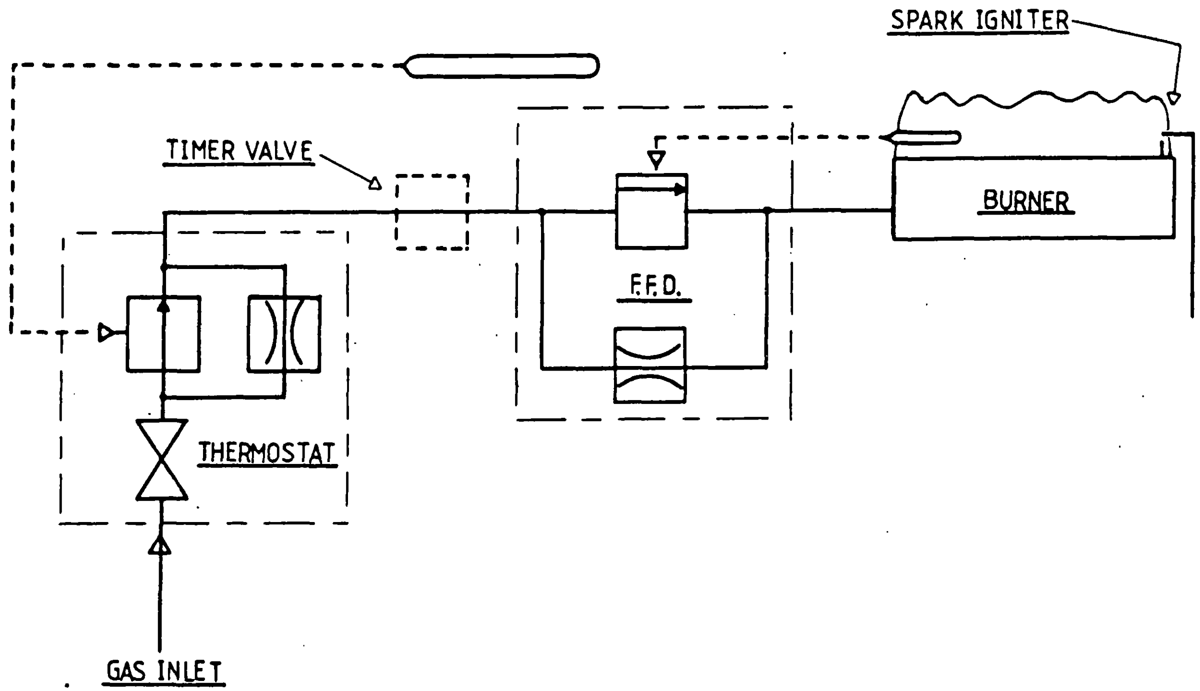
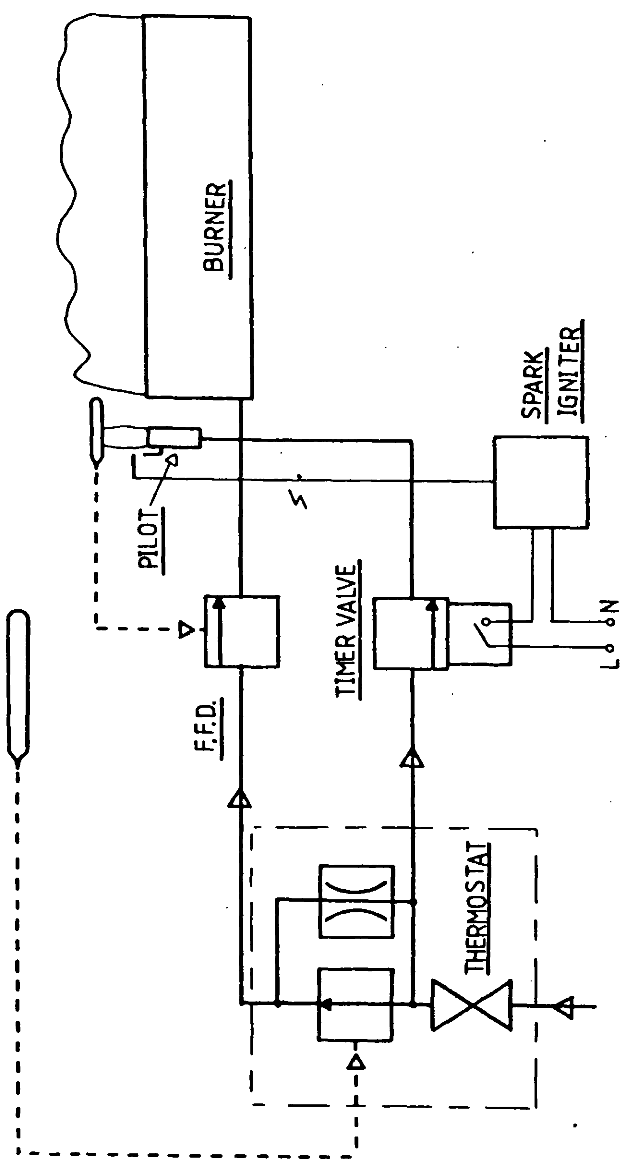


Figure 7



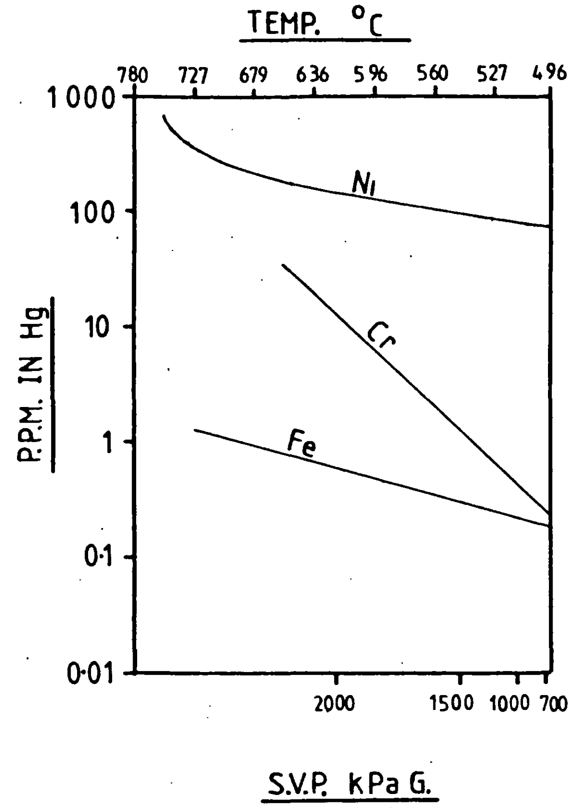
Bypass type oven control system.

Figure 8



Non-bypass type oven control system.

Figure 9

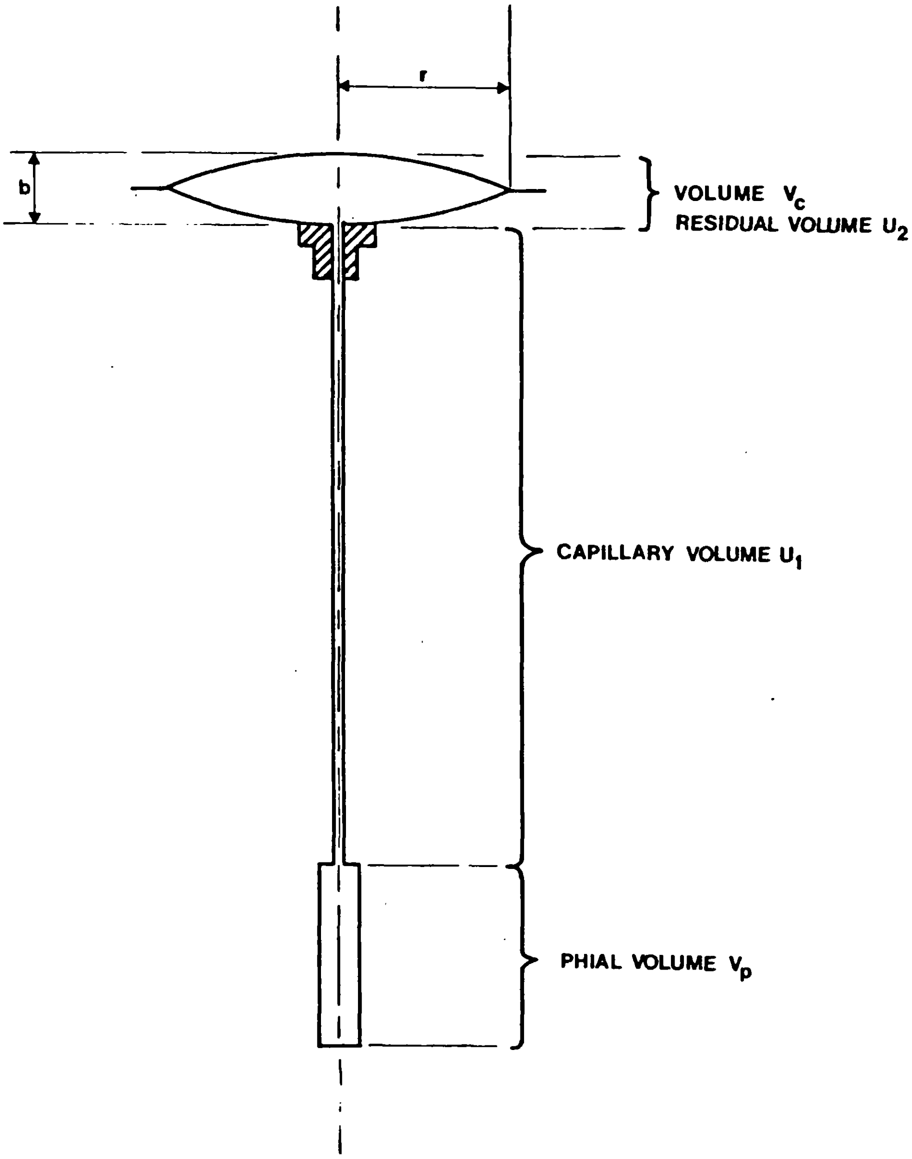


Solubilities of some metals in mercury. Taken from Weeks (30).

Figure 10

Condition of the inside of a mercury F.F.D. phial after 3388 hours continuous running. The lighter regions are where erosion and deposition have occurred.

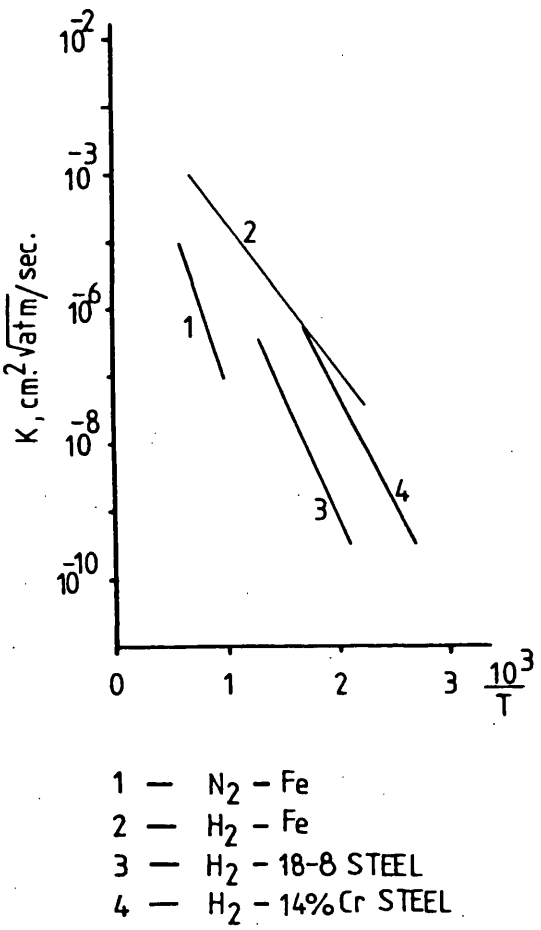
Figure 11



Model of a gas filled thermal system.

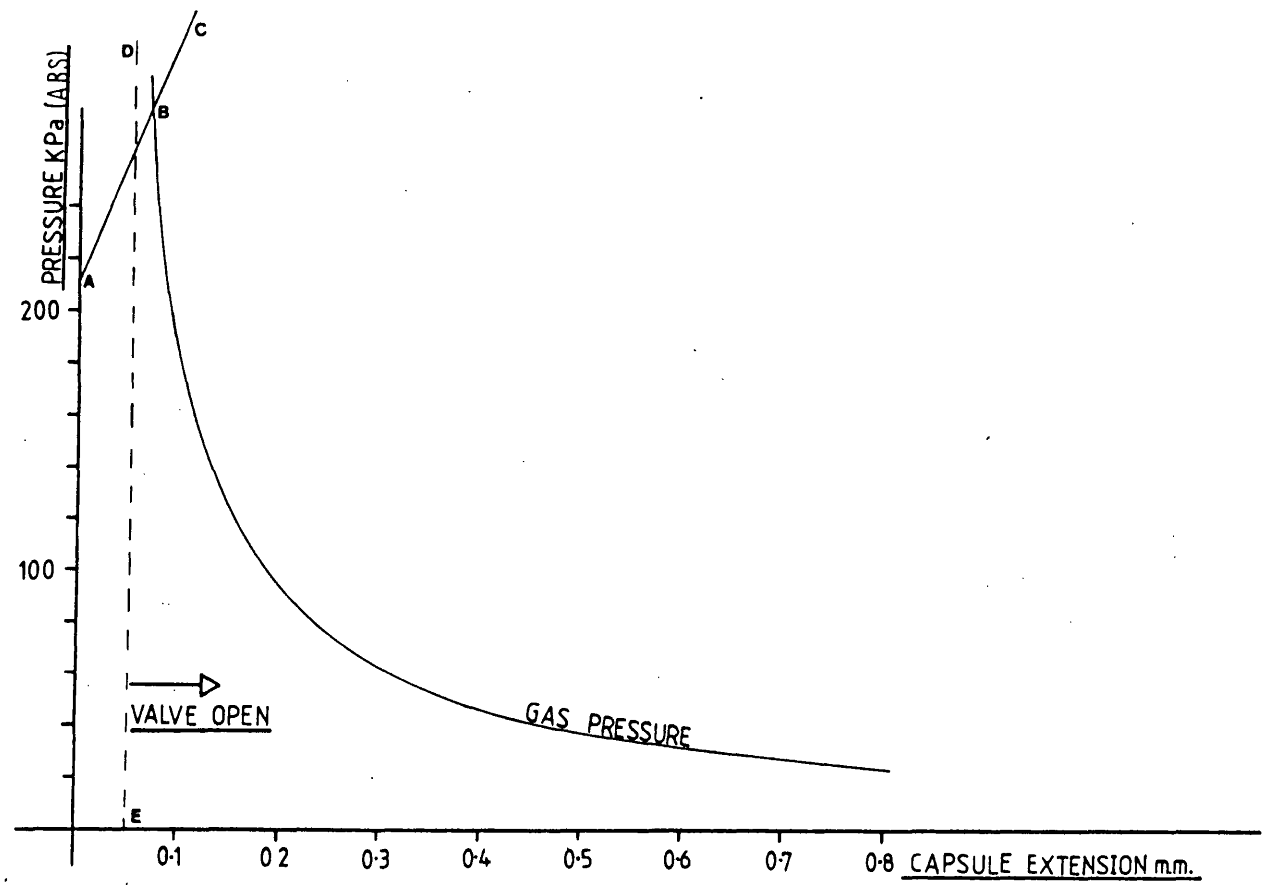
Total dead volume = $U_1 + U_2 = U$

Figure 12



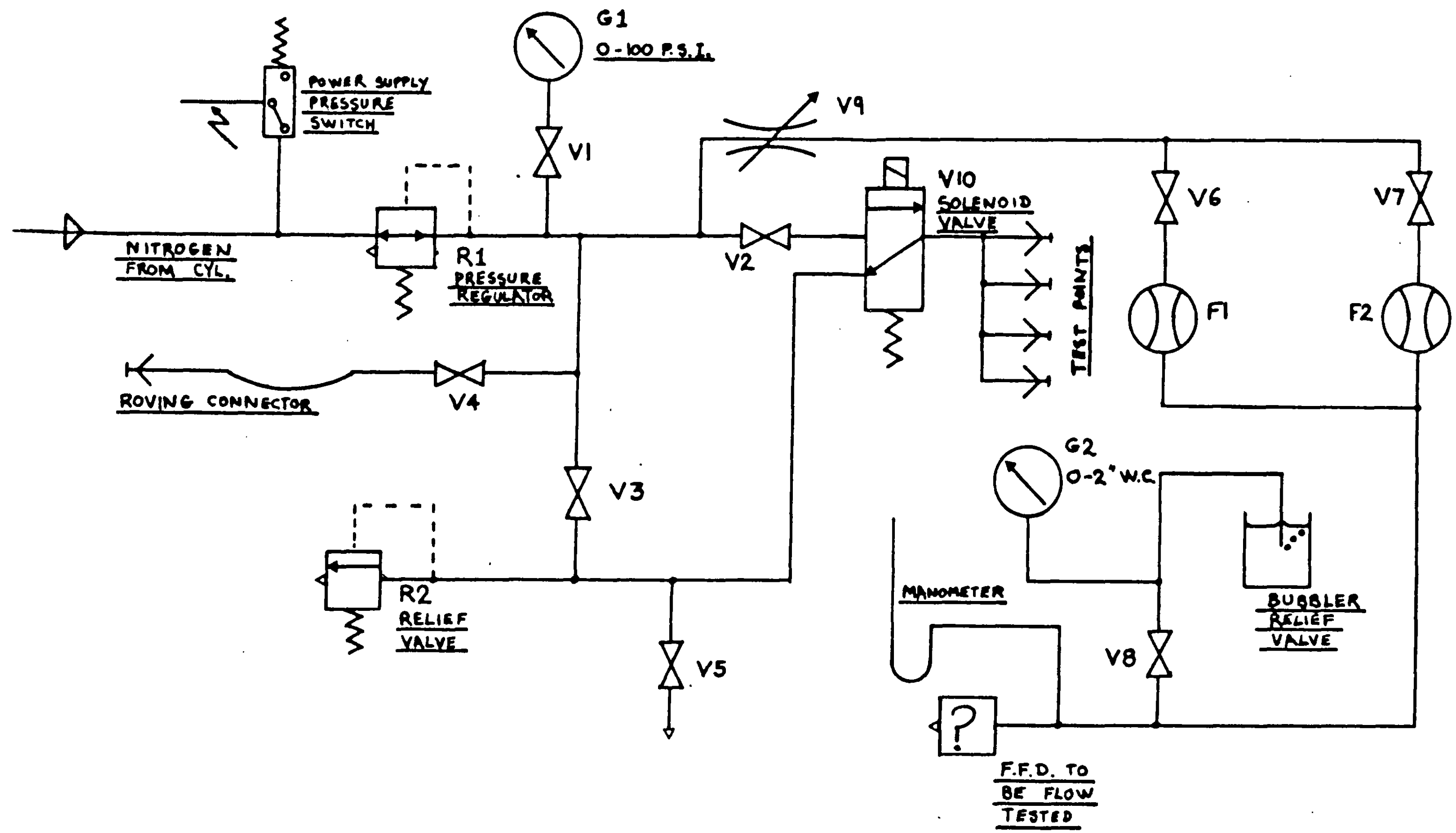
Permeation constants for various gas - metal combinations.
Taken from Redhead et al (54).

Figure 13



The 27 ^{o}C pressure variation of gas which permeated to an equilibrium of 79 kPa at 700 ^{o}C in a Harper Wyman type 5920 mercury F.F.D.

Figure 14



The multi-purpose test rig.

Figure 15

The multi-purpose test rig.

The tube furnace used for thermal system testing can be seen to the far right of the photograph.

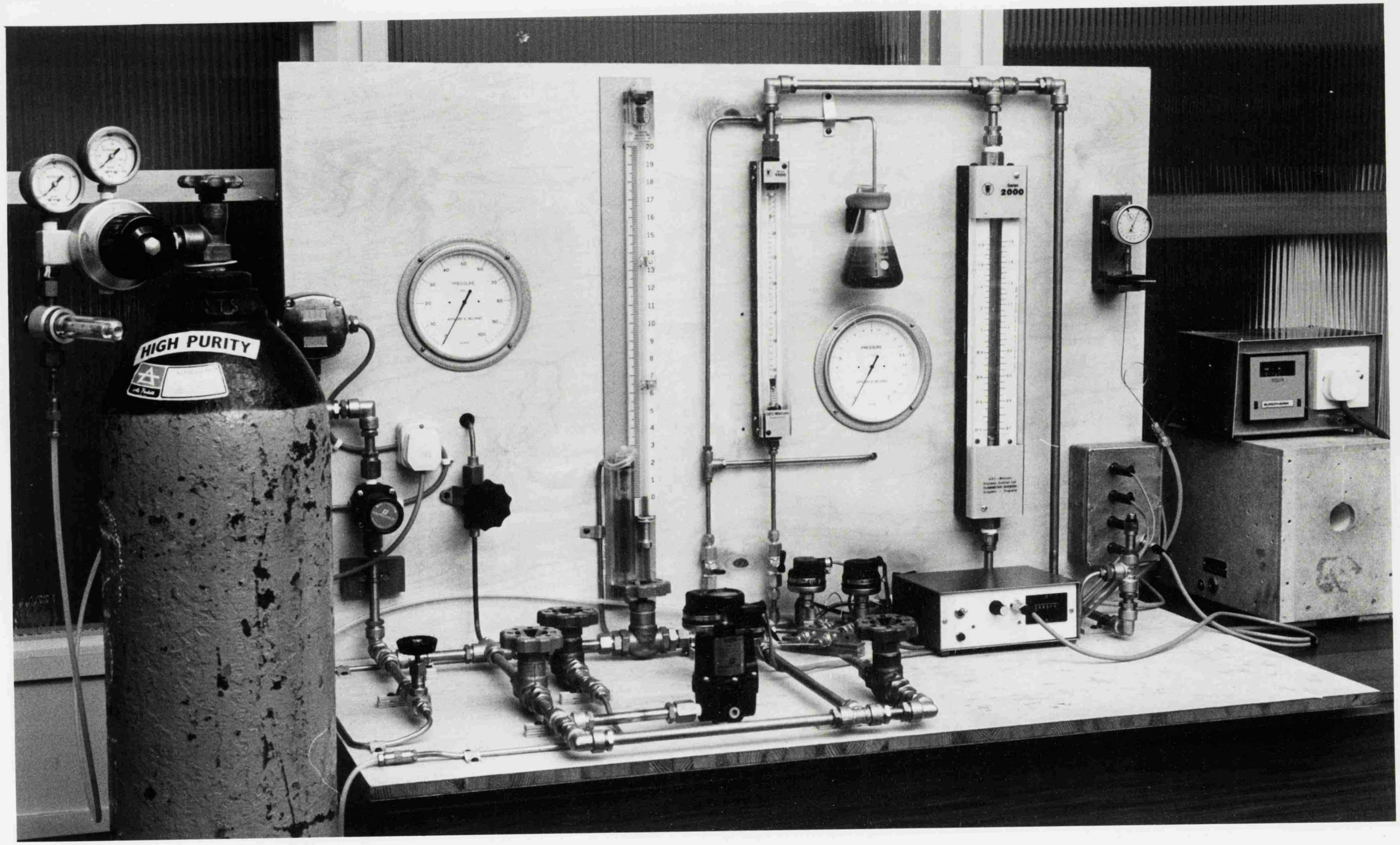
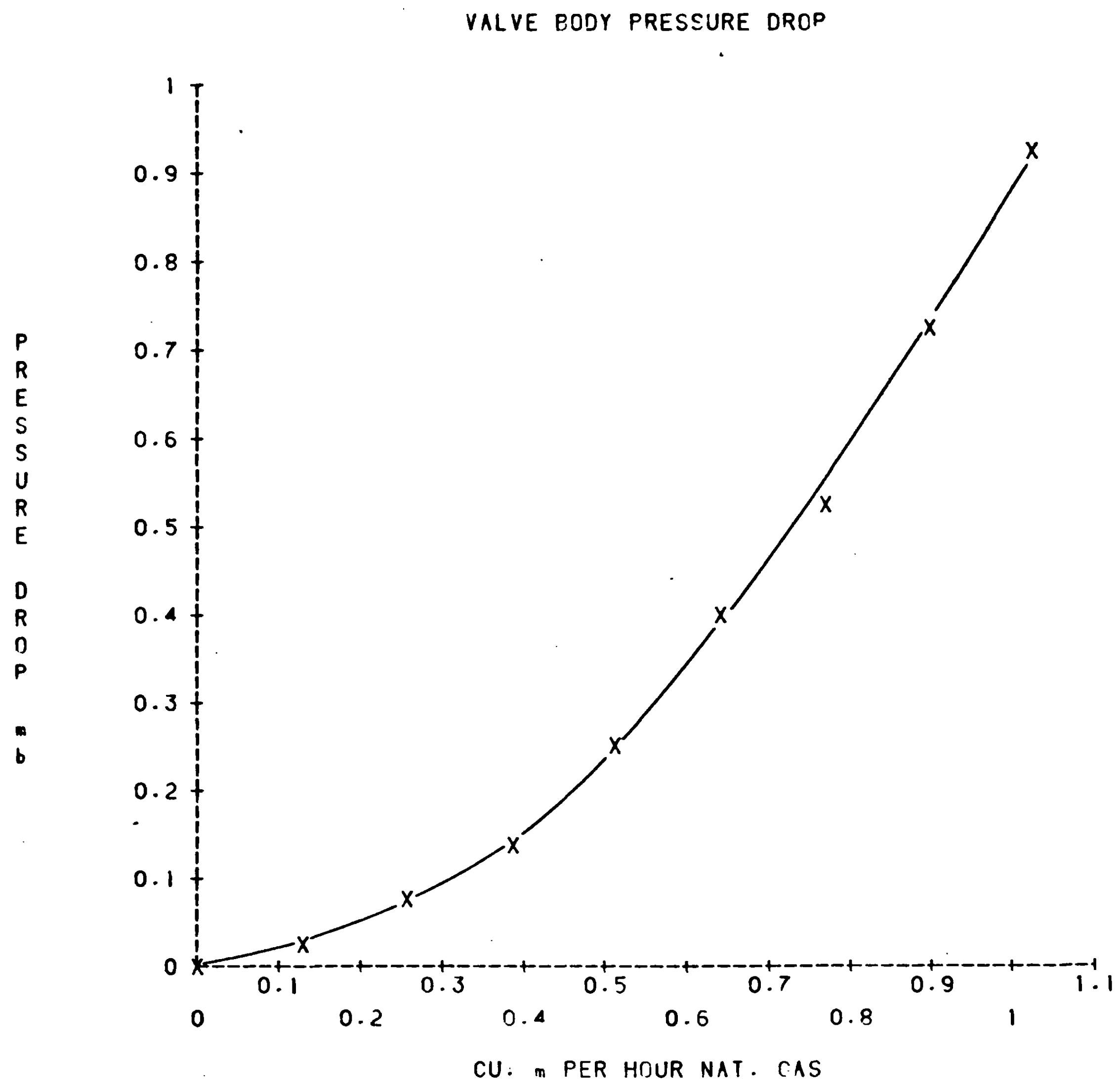
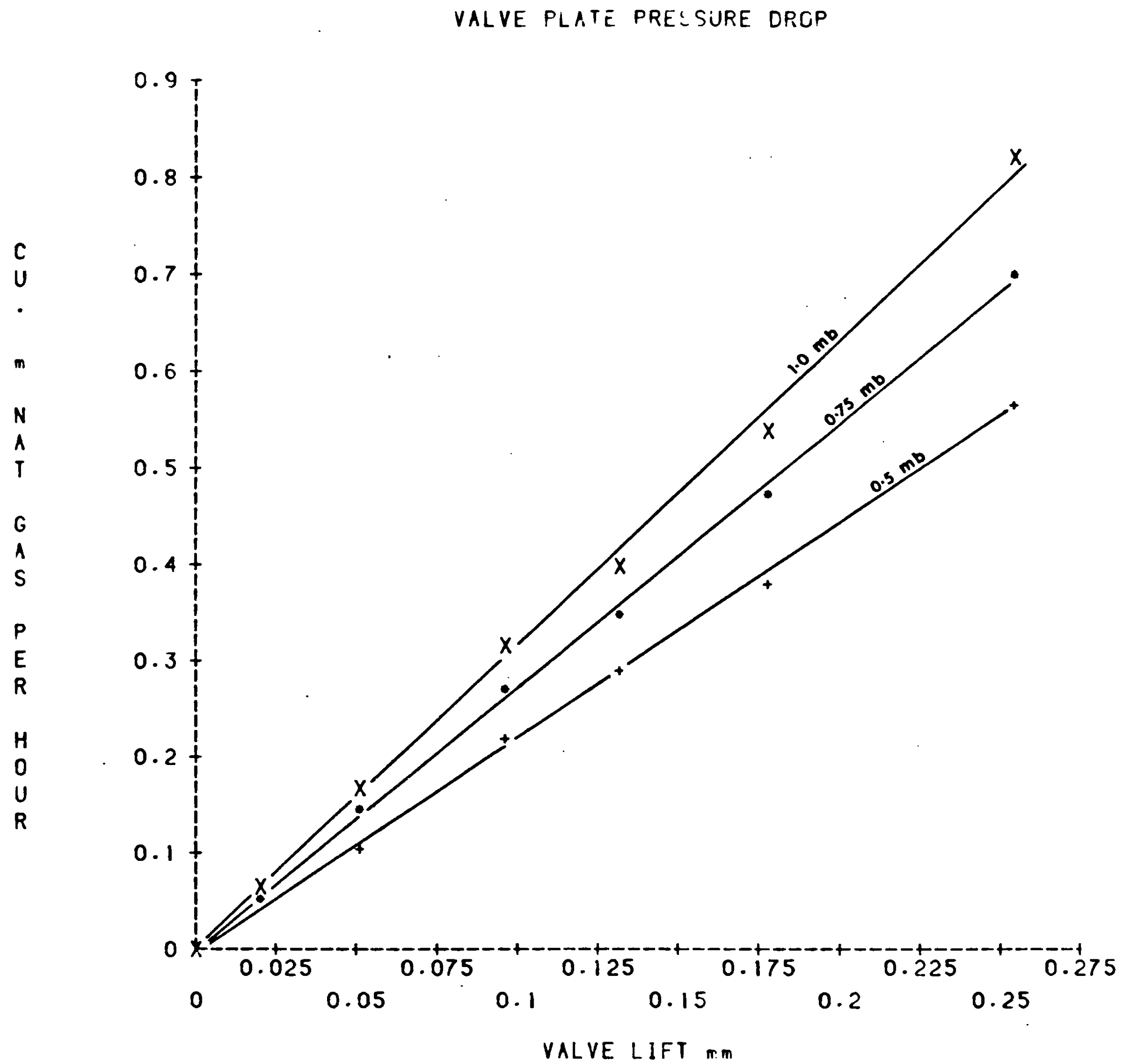

HIGH PURITY

Figure 16



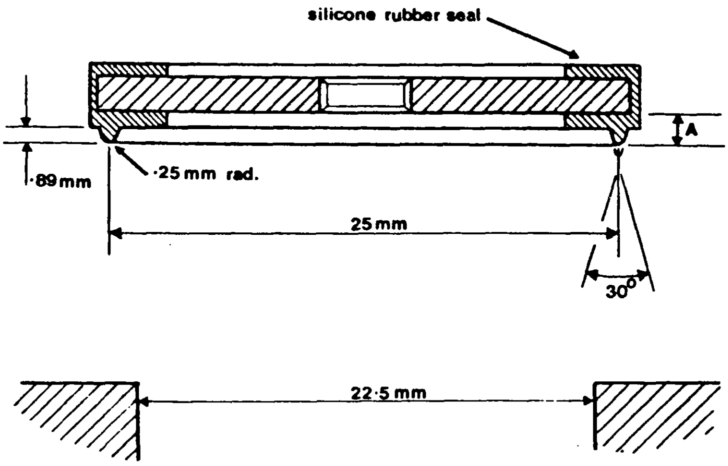
The pressure drop at 0.75 mm valve lift for a ¼" B.S.P. Harper Wyman F.F.D. body.

Figure 17

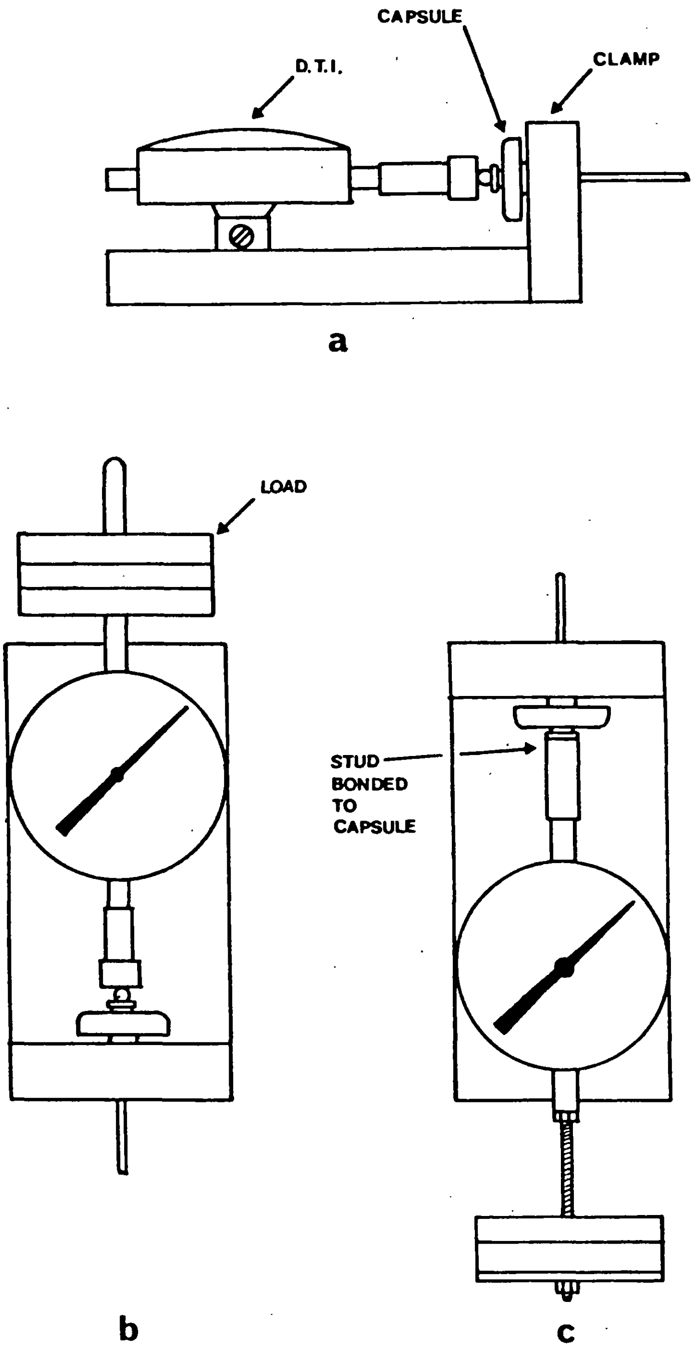


The relationship between gas flow and valve lift at 1.0 mb, 0.75 mb and 0.5 mb pressure drop, for the valve plate and seat shown in fig. 18.

Figure 18



Standard valve plate and seat dimensions.



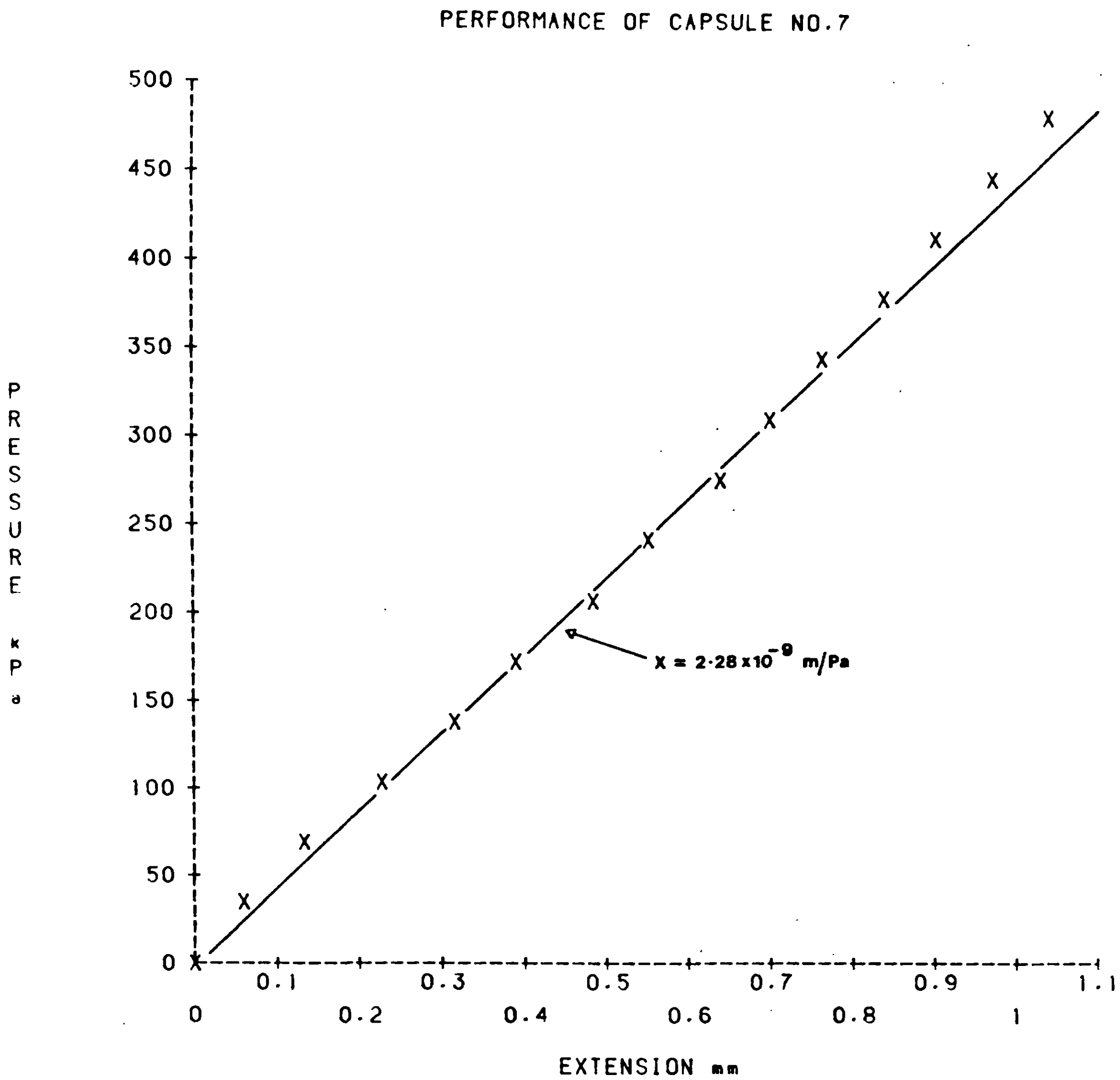
The apparatus for measuring capsule extension

a) Under zero load

b) Under positive loads

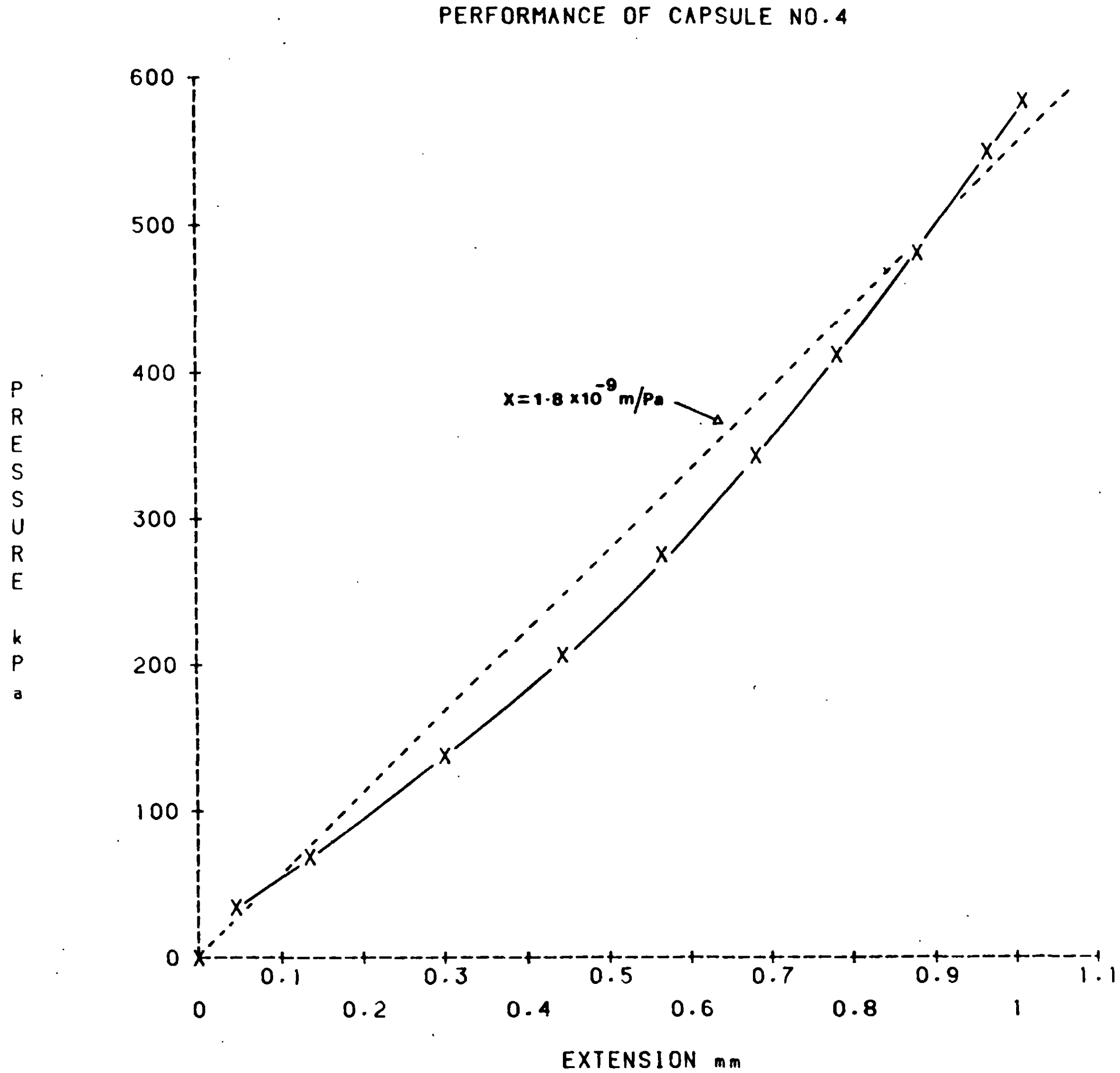
c) Under negative loads.

Figure 20



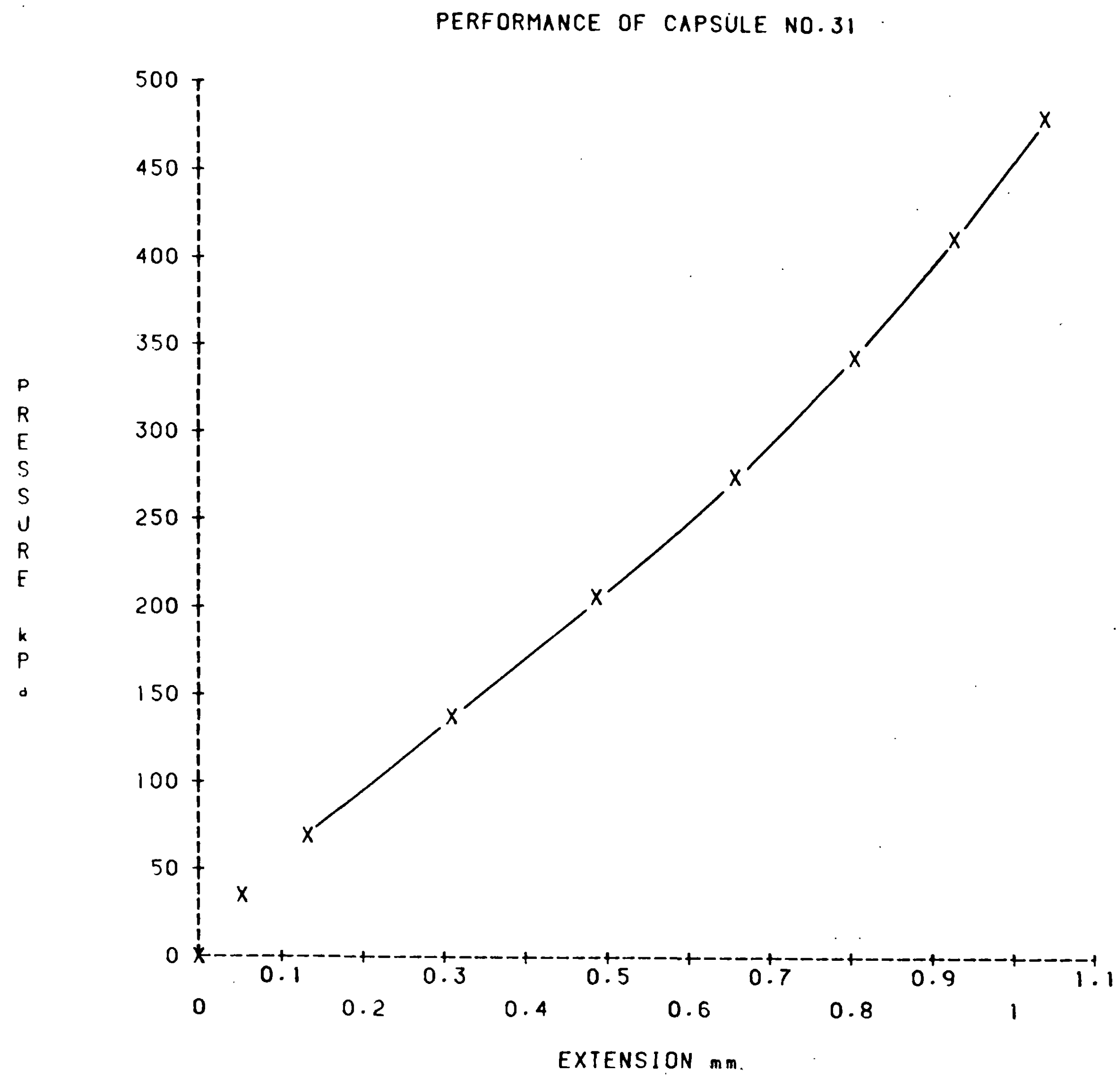
Pressure-extension performance of the capsule used in thermal system number 7.

Figure 21



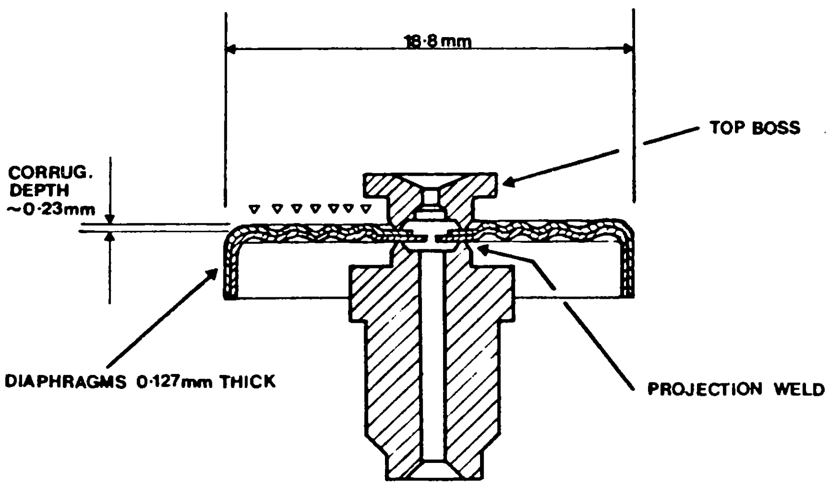
Pressure-extension performance of the capsule used in thermal system number 4.

Figure 22



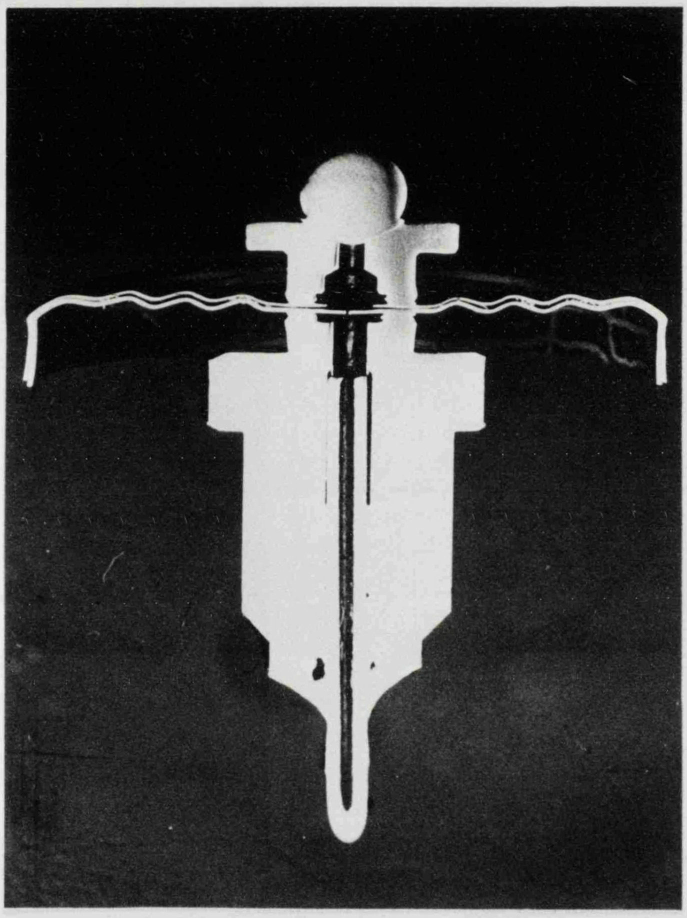
Pressure-extension performance of the capsule used in thermal system number 31.

Figure 23



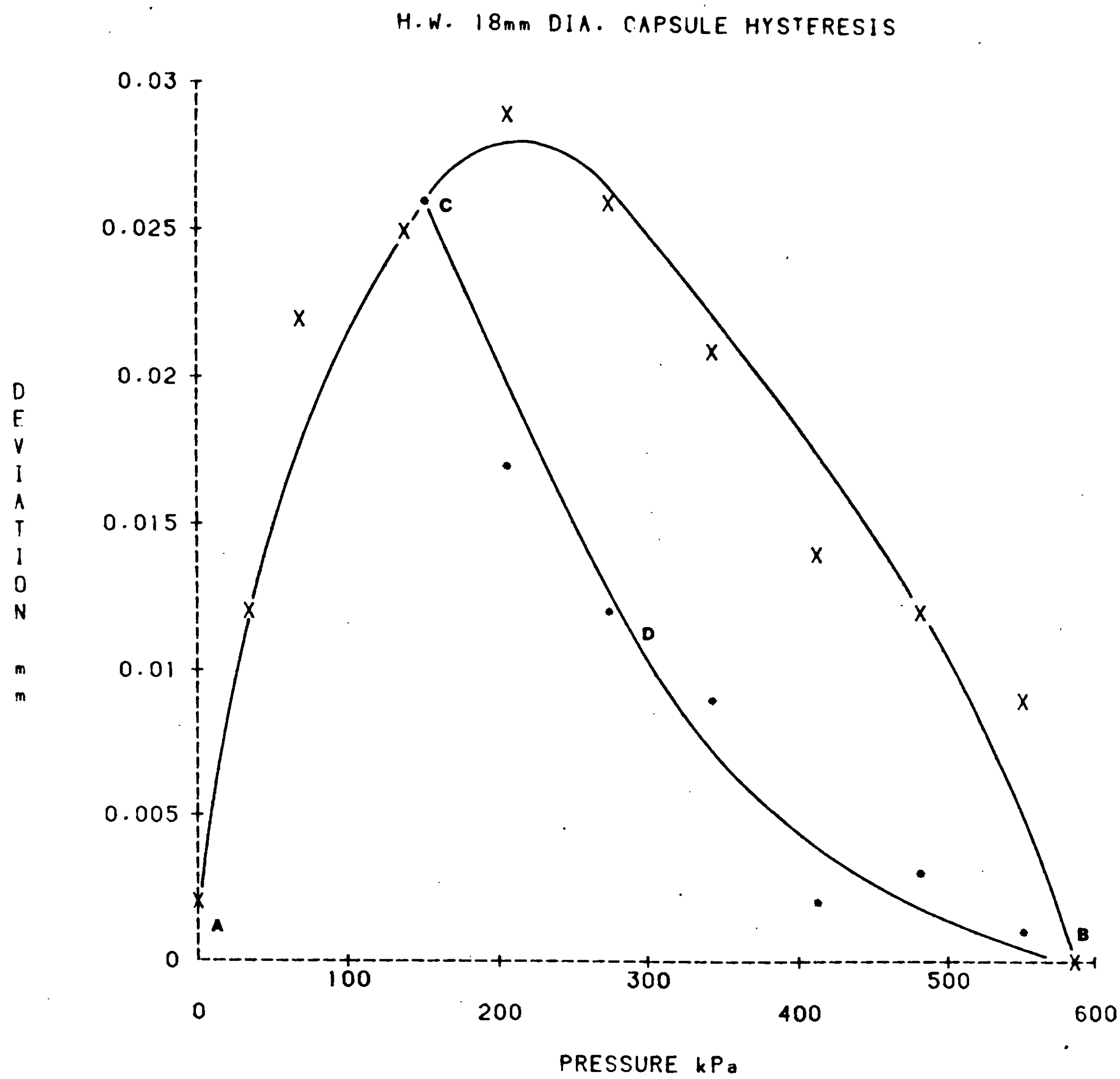
Standard 18 mm diameter Harper Wyman capsule.
∇ indicates the positions where diaphragm thickness measurements were made (see section 7.7).

Figure 24

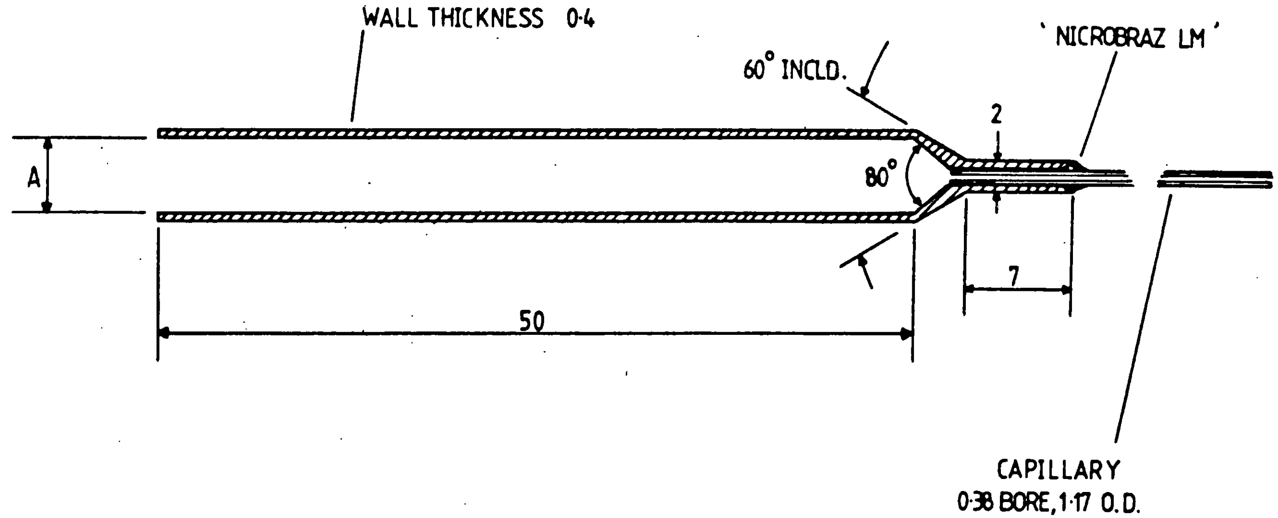


Section through a standard Harper Wyman 18 mm diameter mercury F.F.D. capsule.

Figure 25



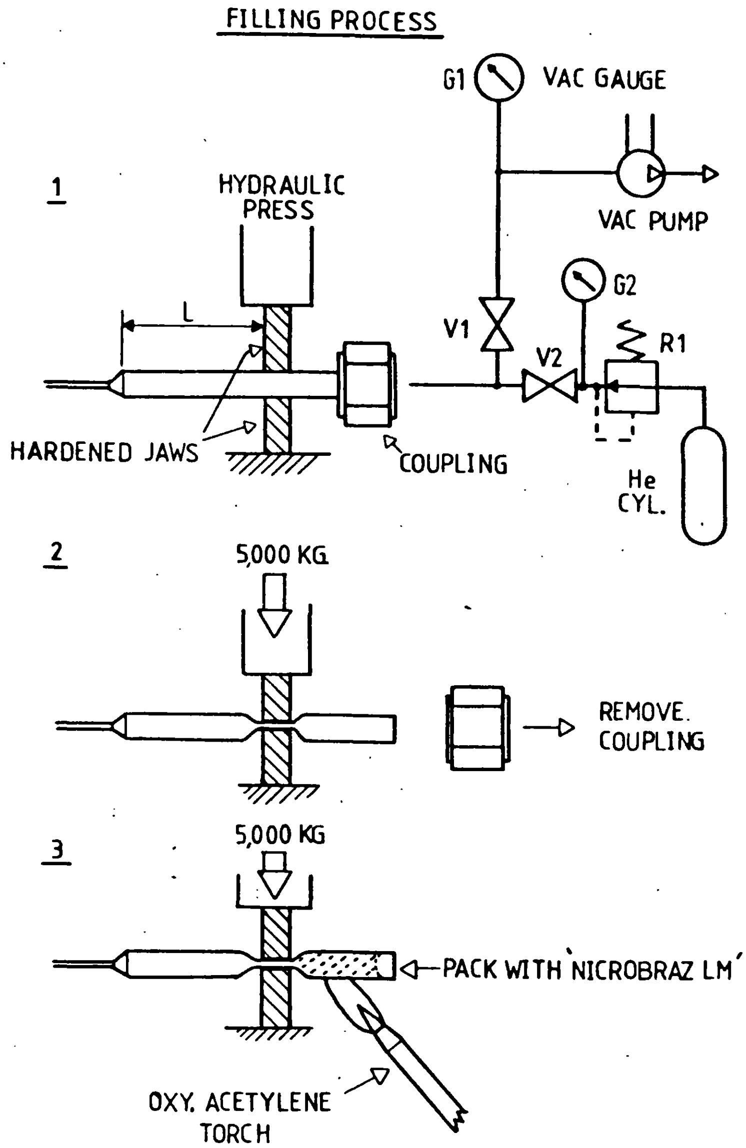
Hysteresis measurements for a standard Harper Wyman 18 mm A.I.S.I. 302 capsule.
Crosses indicate difference between extensions measured when increasing pressure from those measured when decreasing pressure.
Asterisks indicate deviation from increasing pressure extension readings, after pressurization to 586 kPa, reducing pressure to 152 kPa and then re-increasing pressure and measuring extensions.



Experimental phial assembly.

A = 4 mm. Nominal volume 300 mm^3

A = 5 mm. Nominal volume 500 mm^3



Method used to fill experimental thermal systems.

Figure 28

An experimental gas filled thermal system with a 500 mm^3 phial and a standard 18 mm diameter Harper Wyman capsule.

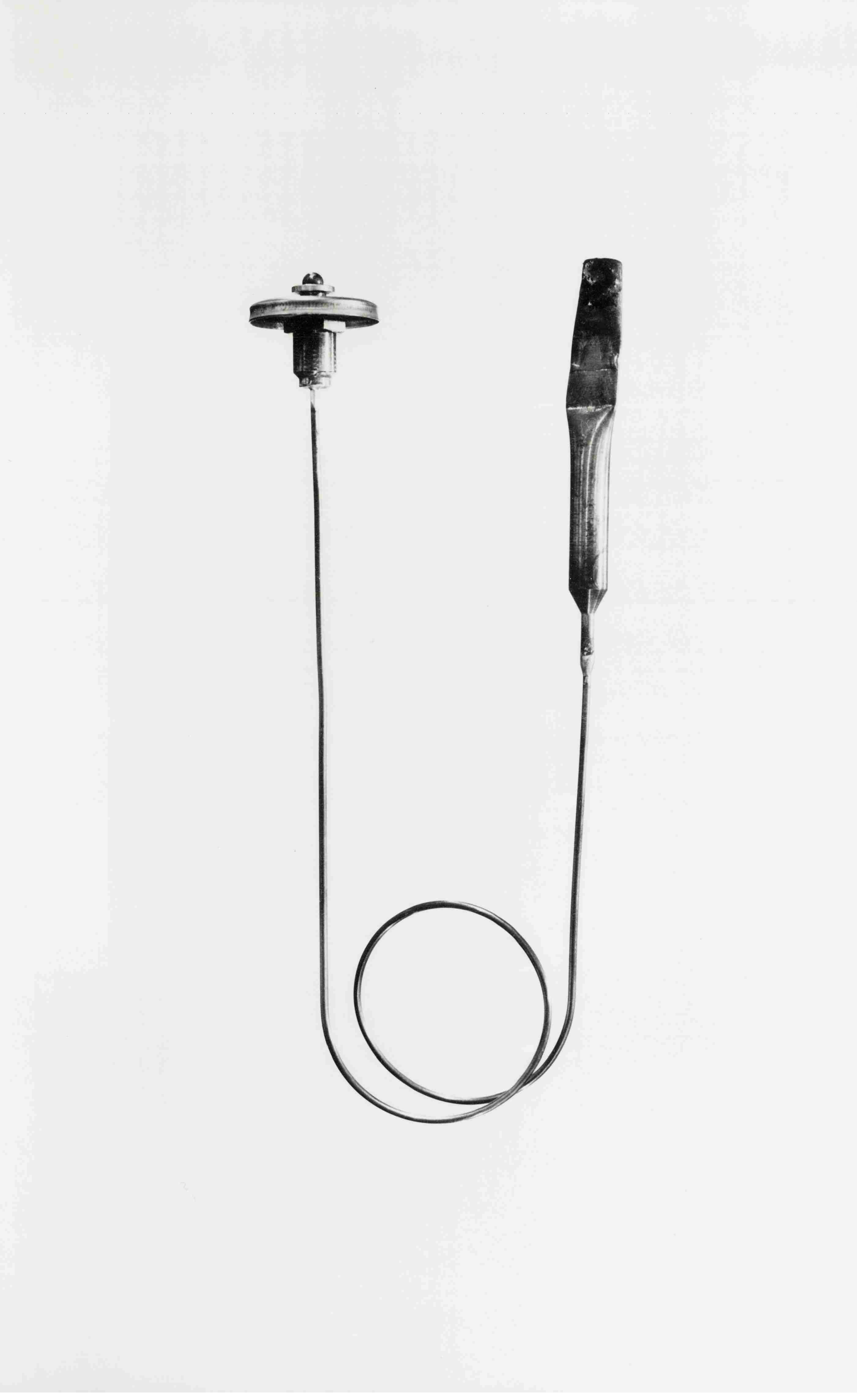
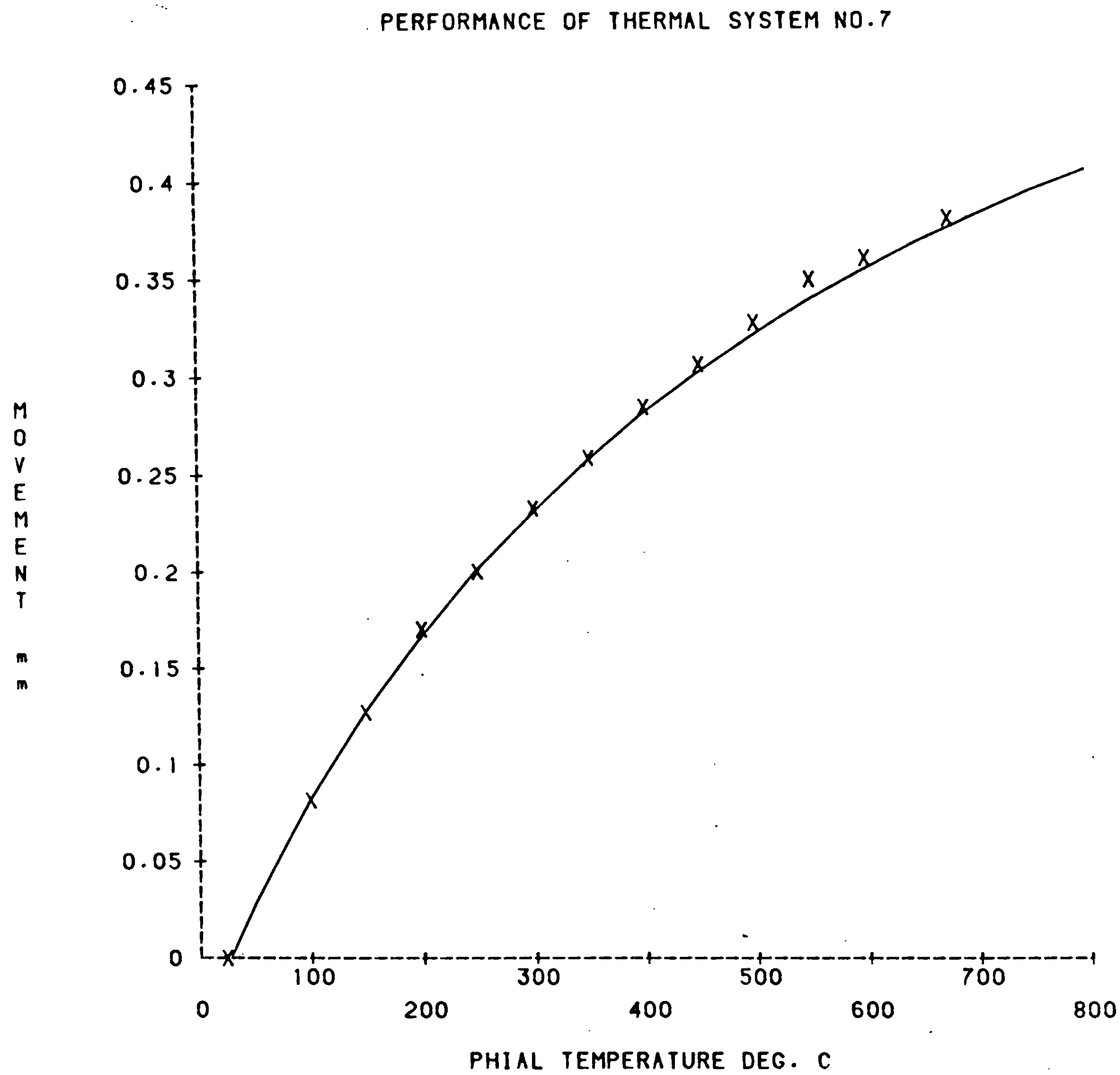


Figure 29



Crosses are experimental measurements.

Line is computed performance prediction based upon:-

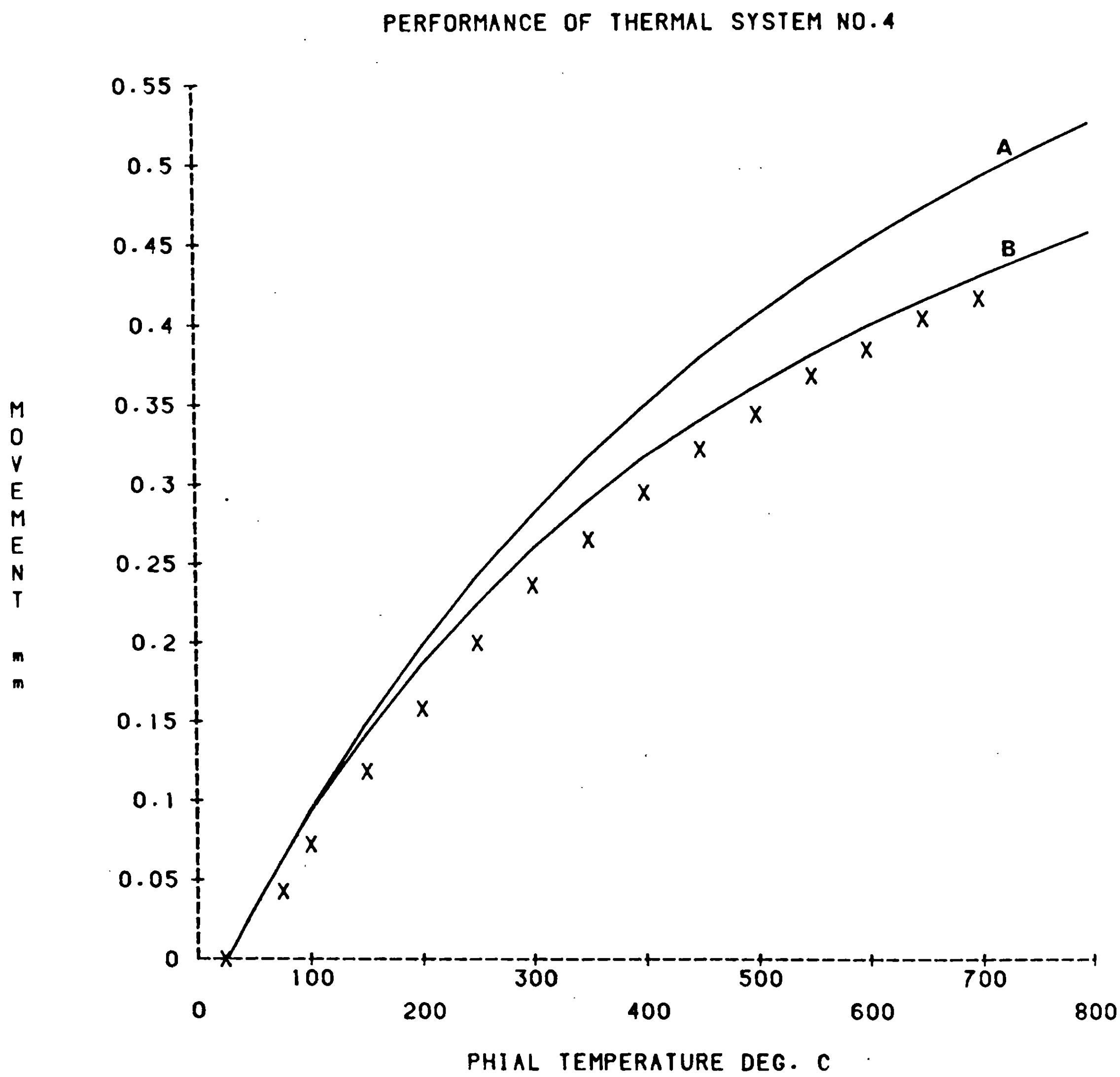
$r = 9$ mm

$V_p = 300$ mm^3

$P_f = 260$ kPa abs.

$U = 59$ mm^3

$X = 2.28 \times 10^{-9}$ m/Pa



Crosses are experimental measurements.

Lines are computed performance predictions based upon:-

$r = 9$ mm

$V_p = 500\ mm^3$

$U = 50\ mm^3$

<u>Curve A</u>

$P_f = 313$ kPa abs.

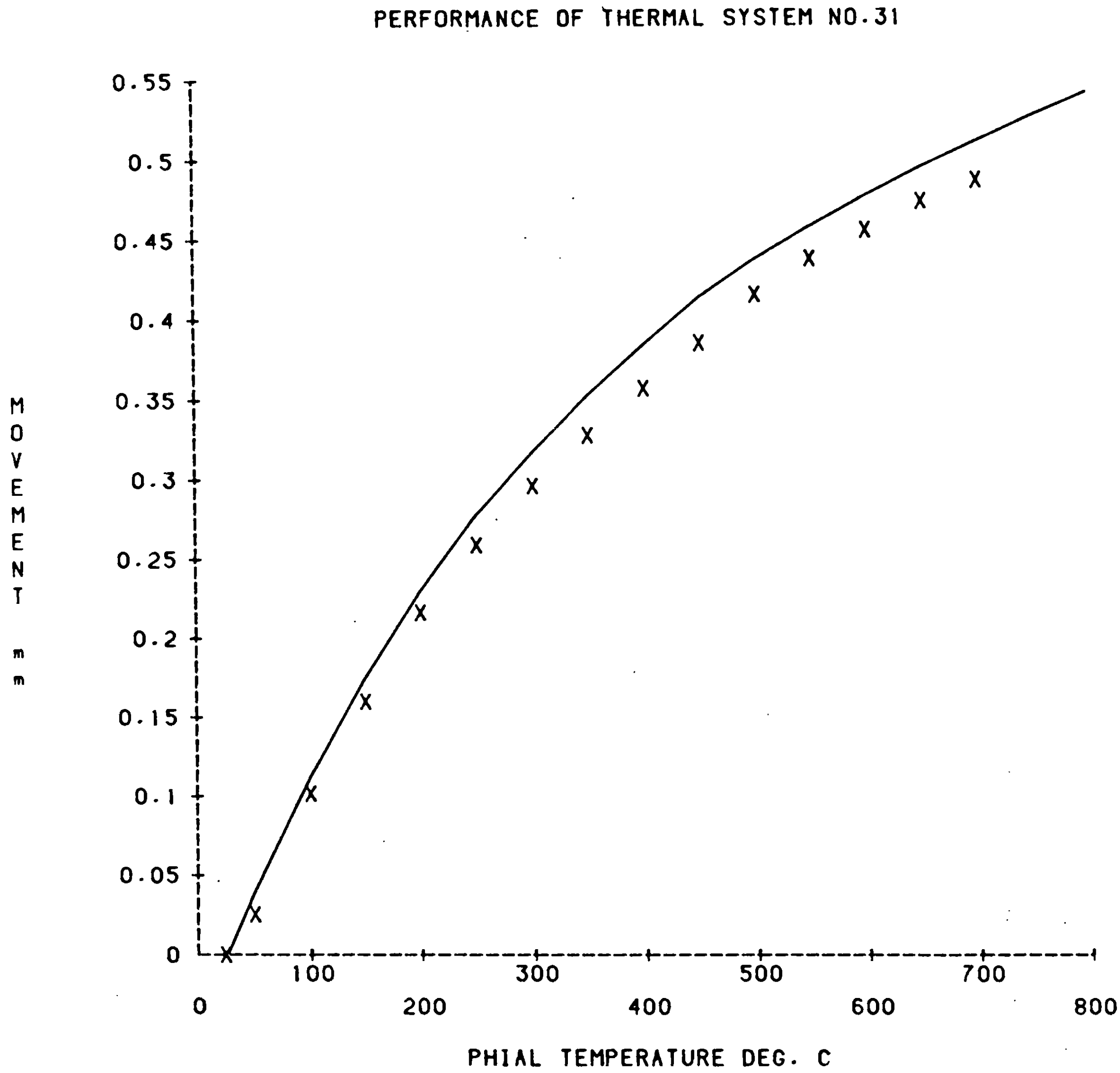
$X = 1.8 \times 10^{-9}$ m/Pa

<u>Curve B</u>

$P_f = 278$ kPa abs.

Pressure-extension data figure 21.

Figure 31



Crosses are experimental measurements.

Line is computed performance prediction based upon:-

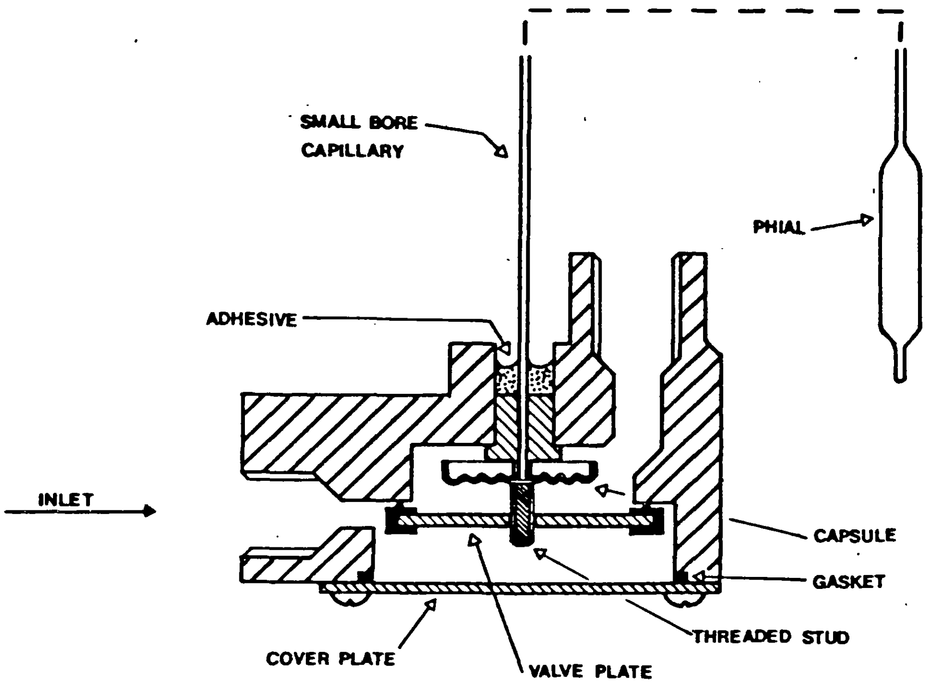
$r = 9$ mm

$V_p = 500$ mm^3

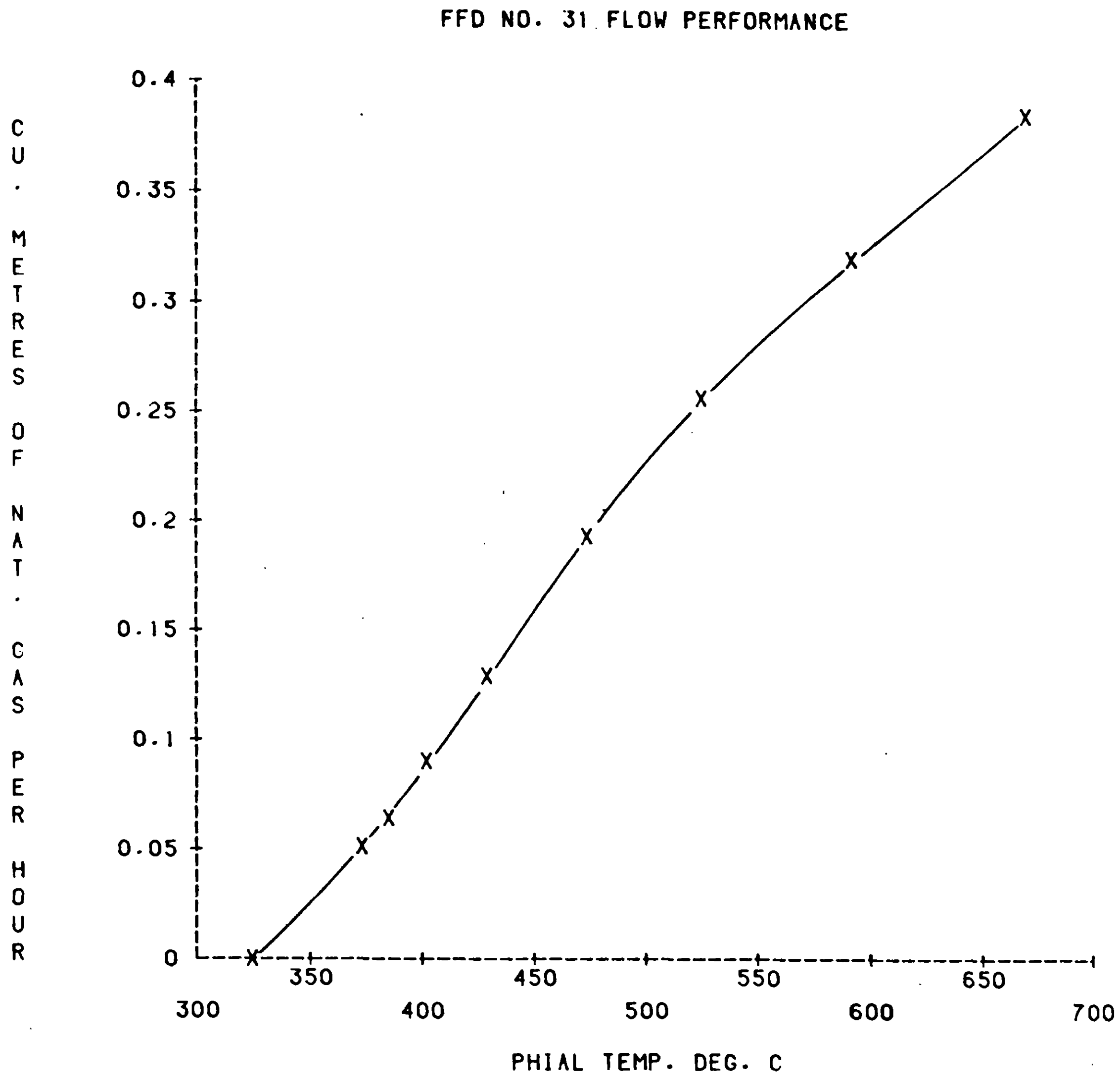
$U = 60$ mm^3

$P_f = 266$ kPa abs.

Pressure-extension data figure 22.



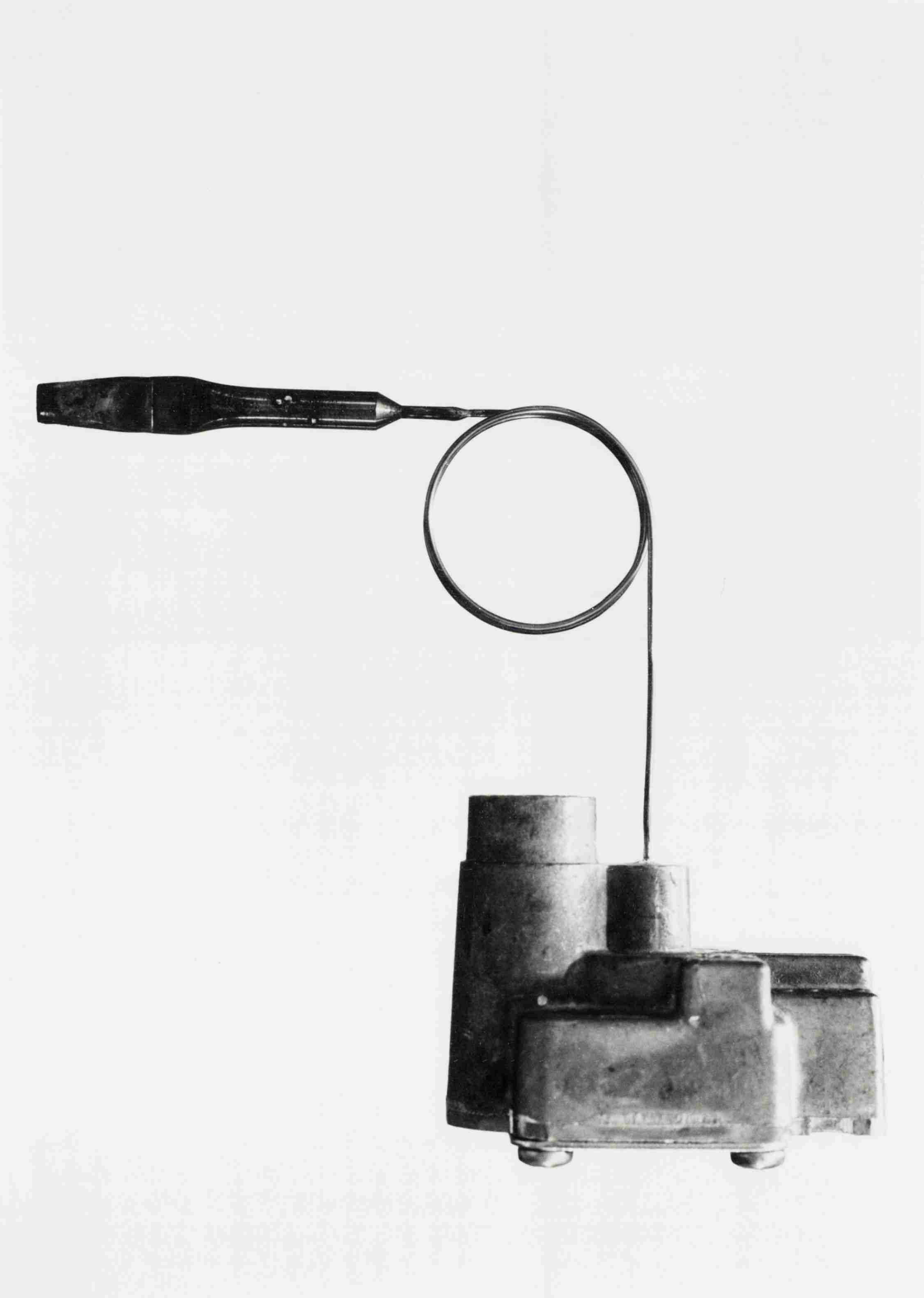
A schematic diagram of an experimental gas filled flame failure device.

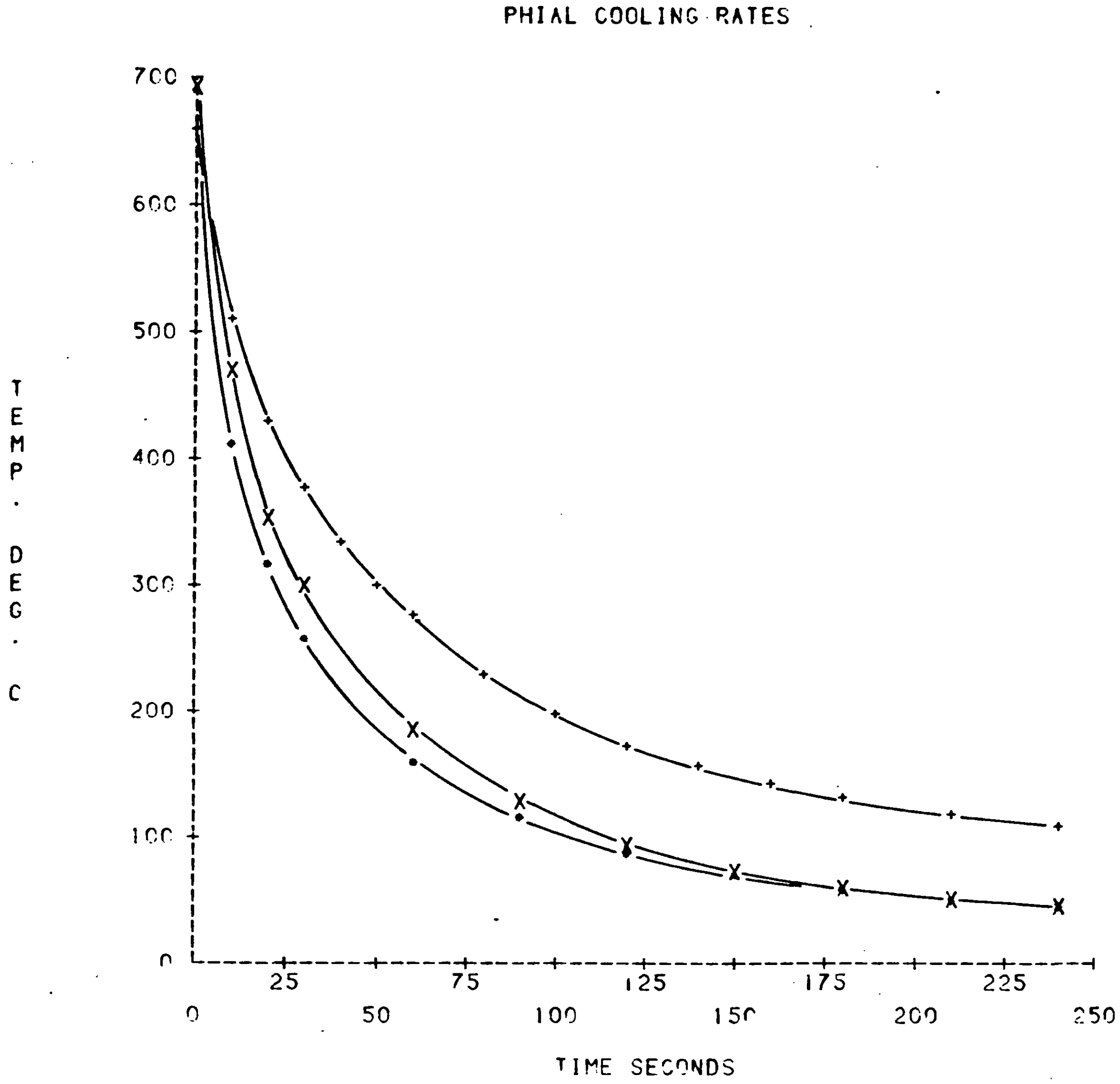


Flow performance of experimental F.F.D. number 31 at 0.75 mb pressure differential.

Figure 34

Photograph of an experimental gas filled flame failure device with a 500 mm^3 phial.





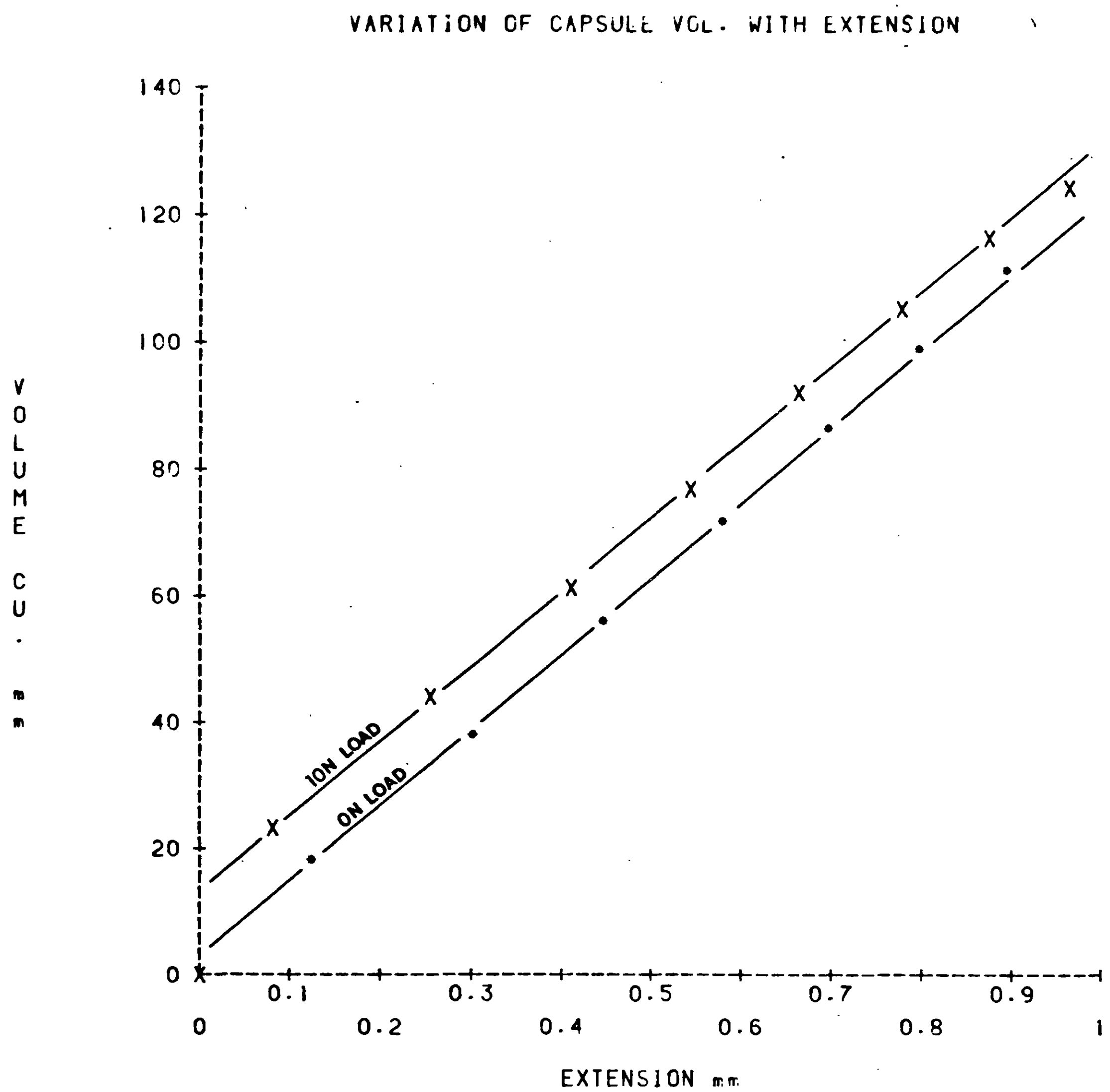
The cooling rates of experimental F.F.D. phials.

+ 300 mm^3 phial in gas oven at 250 ^oC C.O.T.

X 300 mm^3 phial in air at 22 ^oC

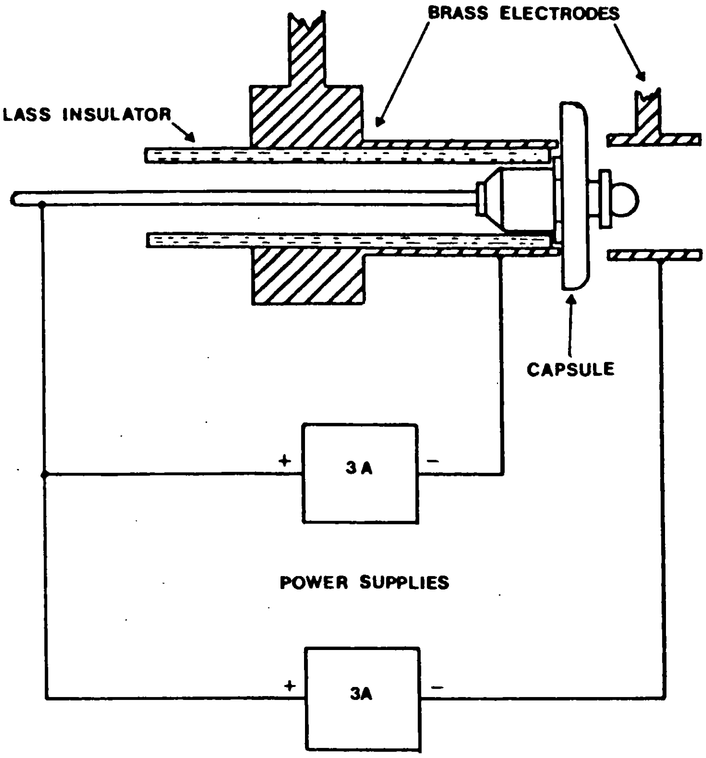
* 500 mm^3 phial in air at 22 ^oC

Figure 36



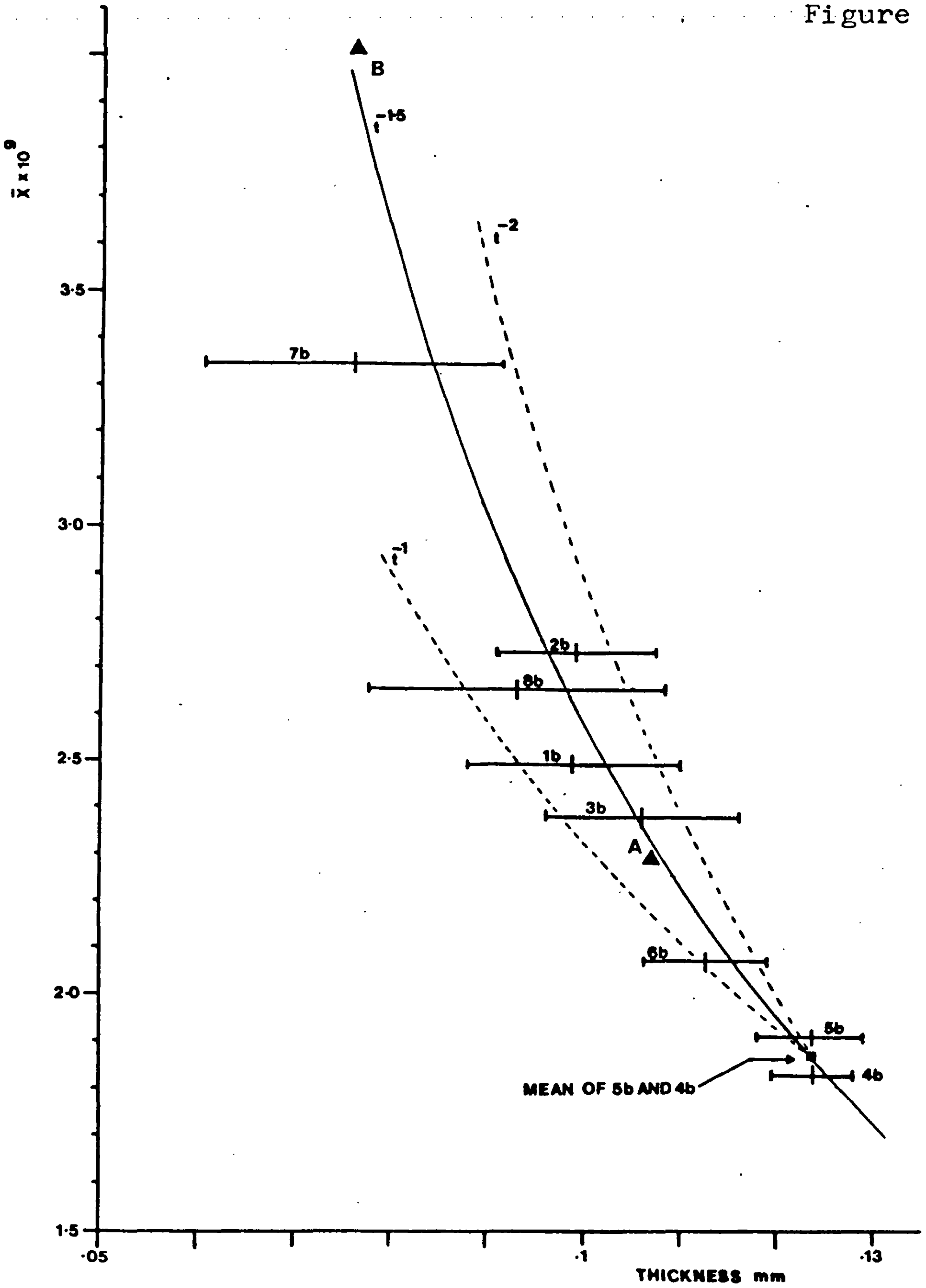
The volume-extension relationship for Harper Wyman 18 mm diameter capsules.

Figure 37

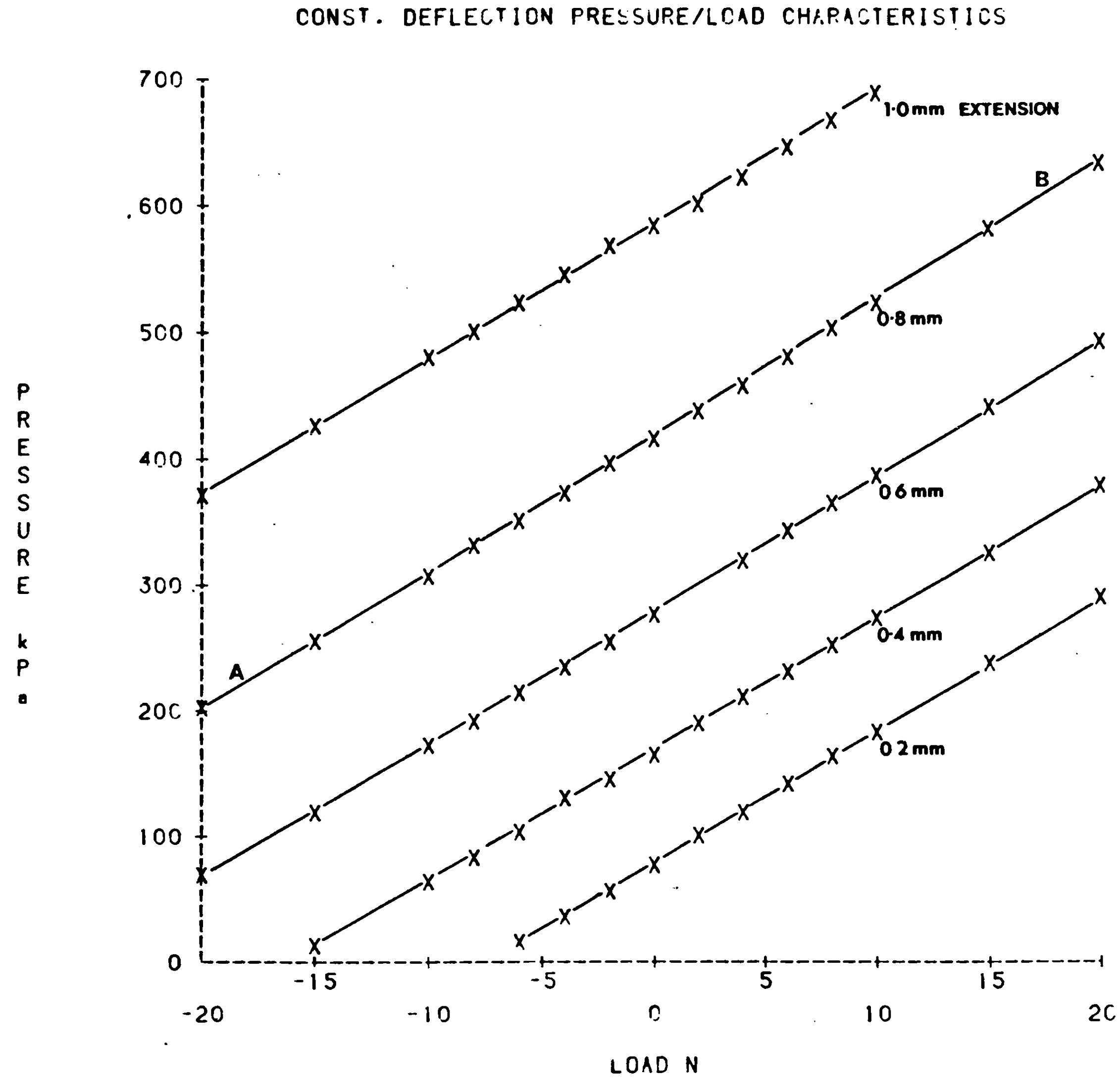


The apparatus used for electropolishing Harper Wyman 18 mm diameter capsules.

Figure 38

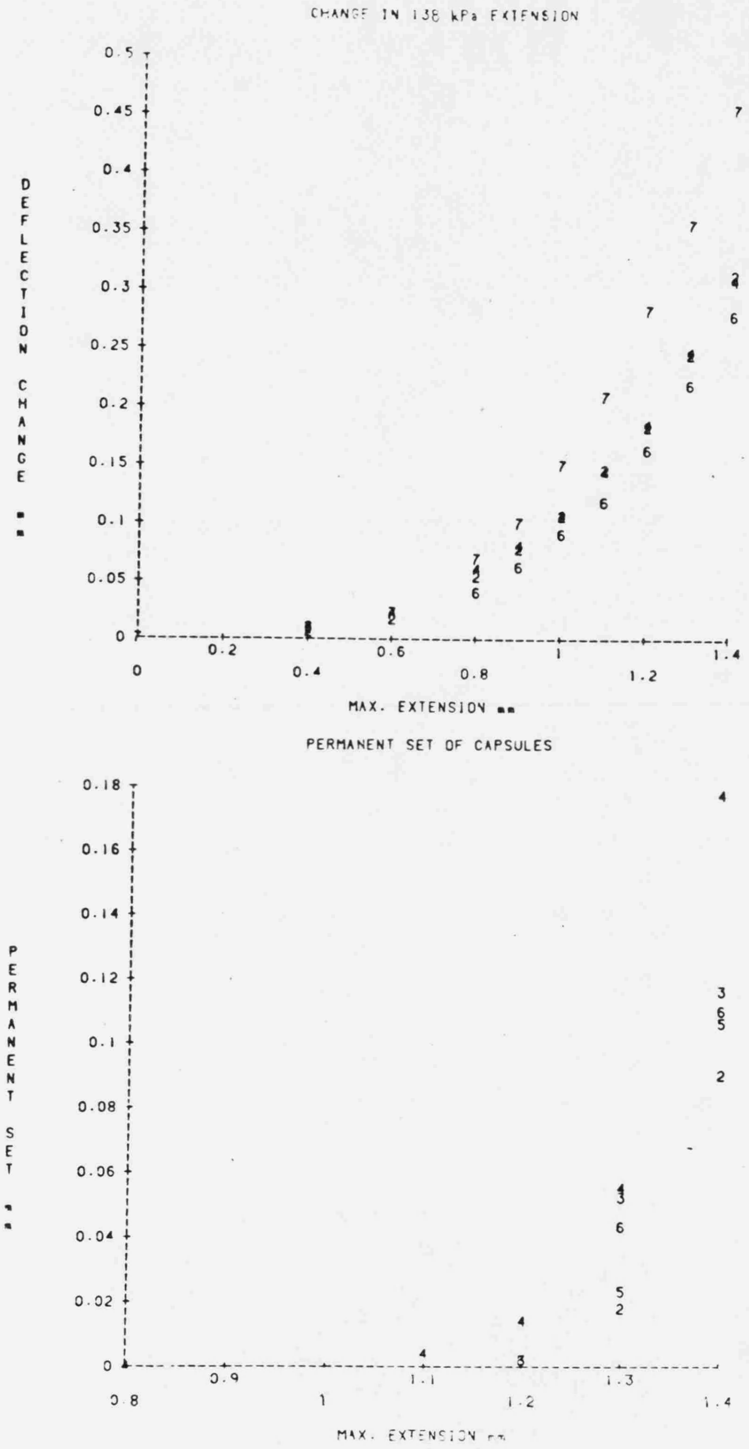


The relationship between the diaphragm thickness and the mean pressure sensitivity of Harper Wyman 18 mm diameter capsules.



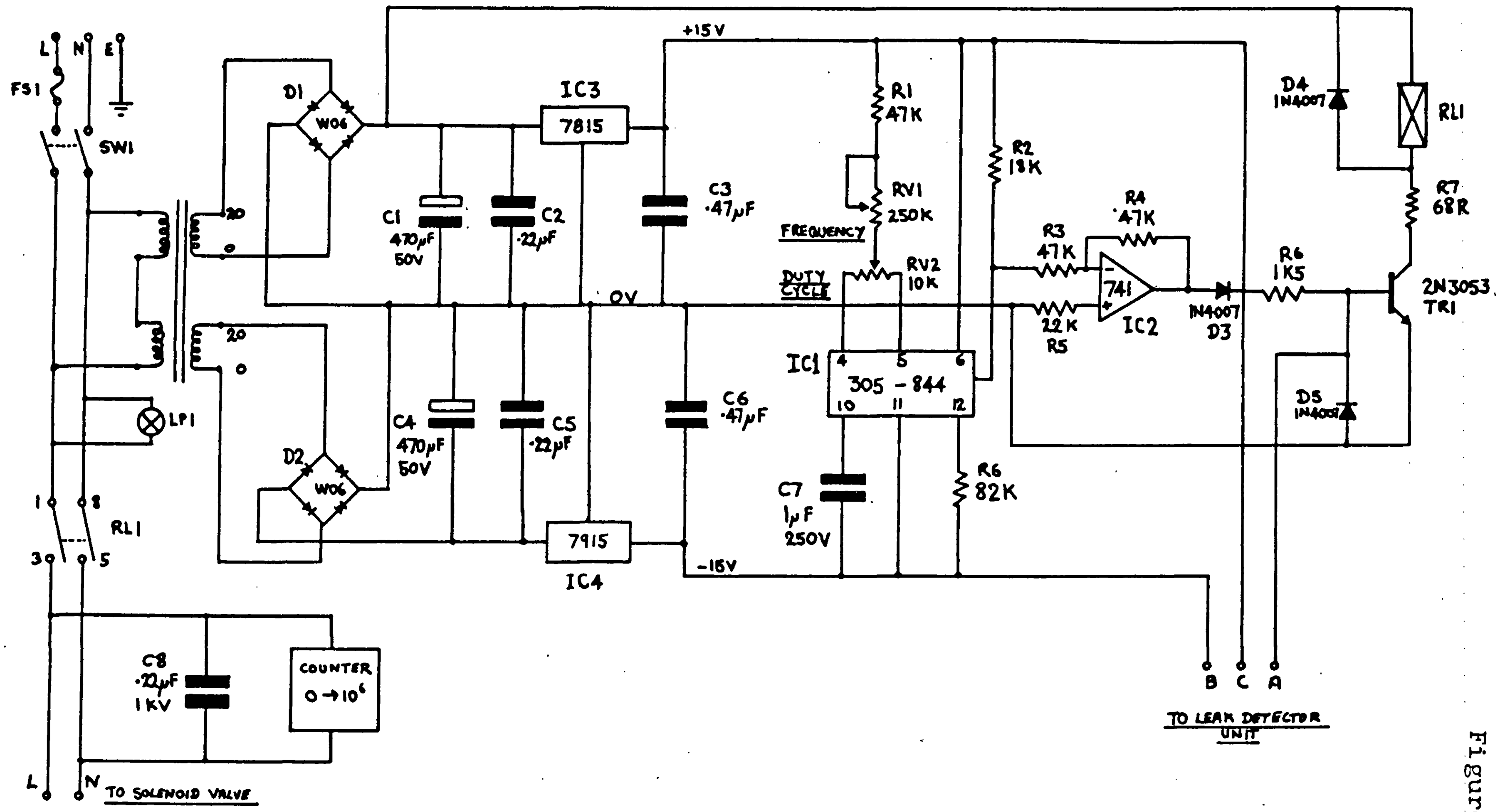
The relationship between pressure and load at constant capsule extension for Harper Wyman 18 mm diameter capsules.

Figure 40



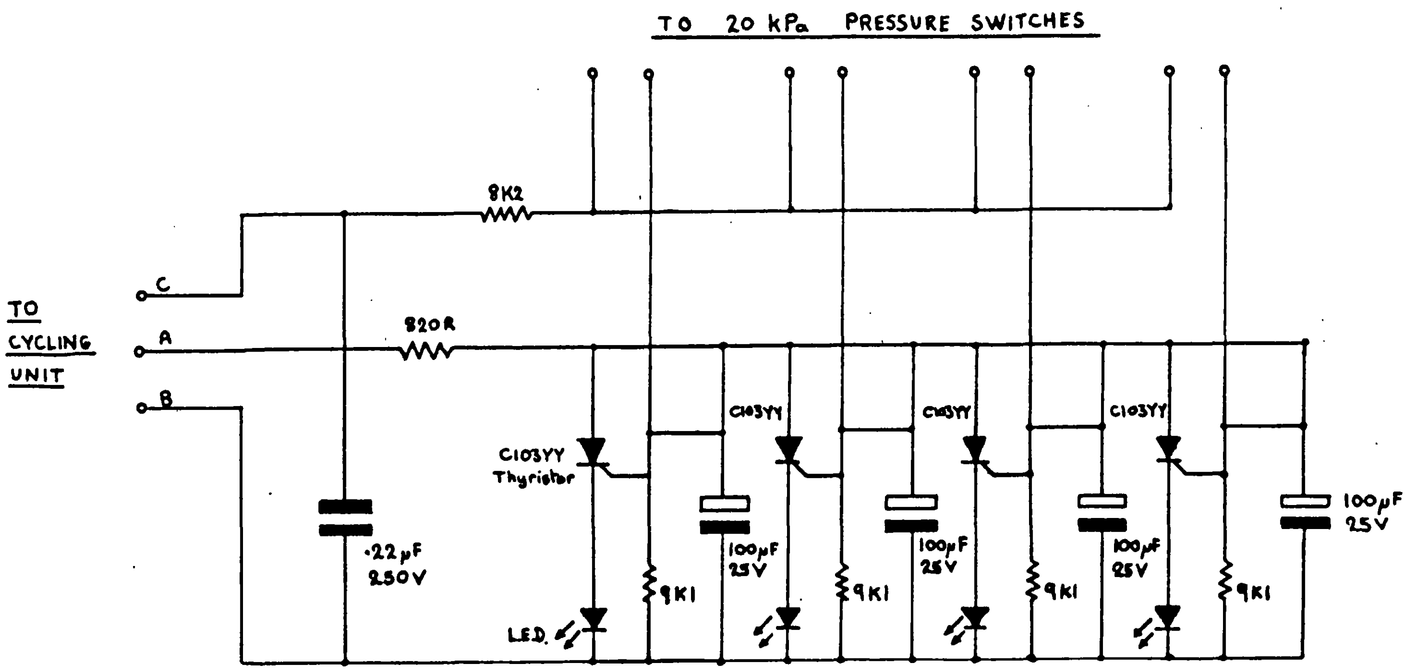
The change in 138 kPa deflection and permanent set of some 18 mm diameter Harper Wyman capsules.
The numerals indicate the sample number

Figure 41



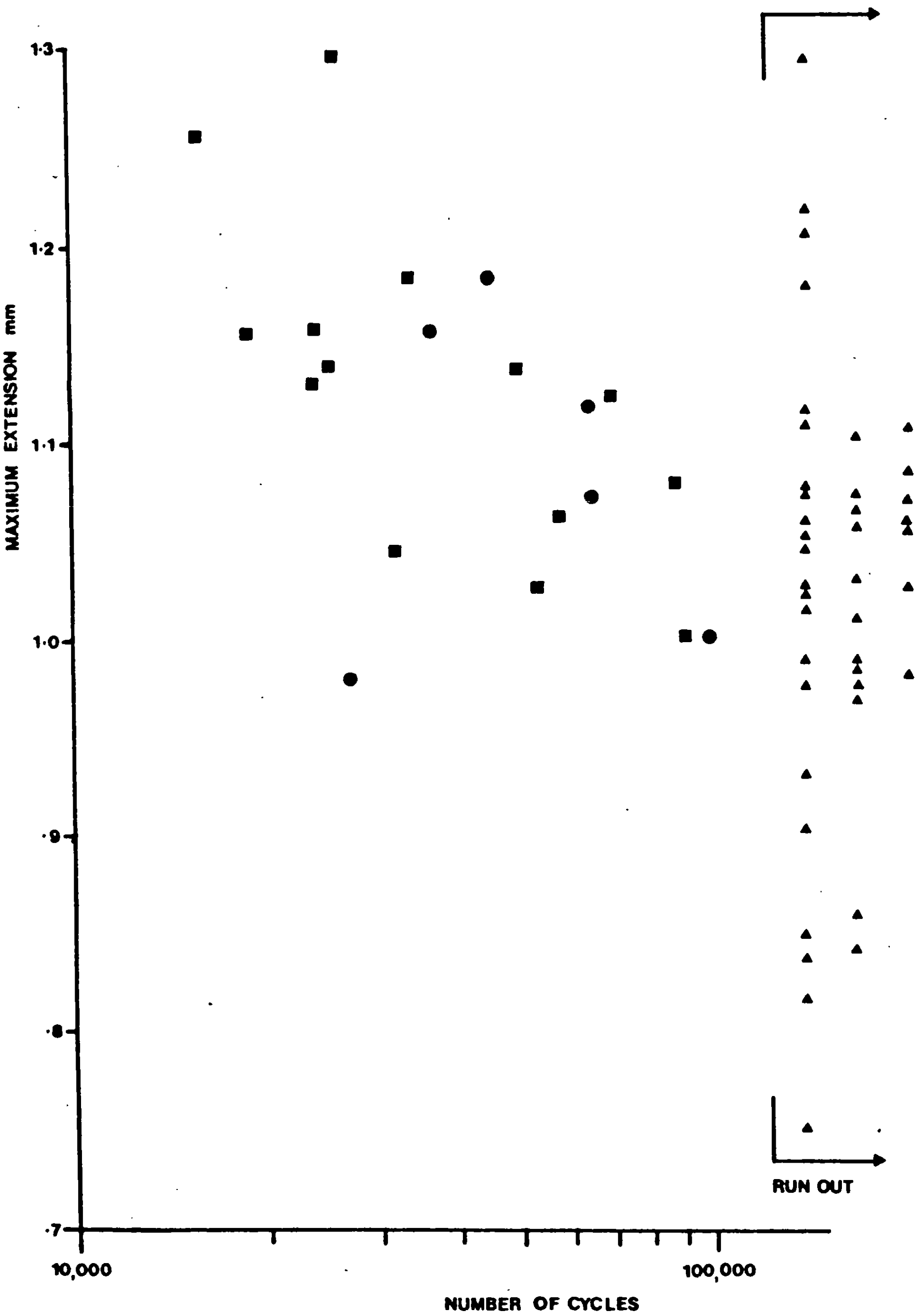
Cycling control unit for capsule fatigue testing rig.

Figure 42



Capsule leak detector unit.

Figure 43

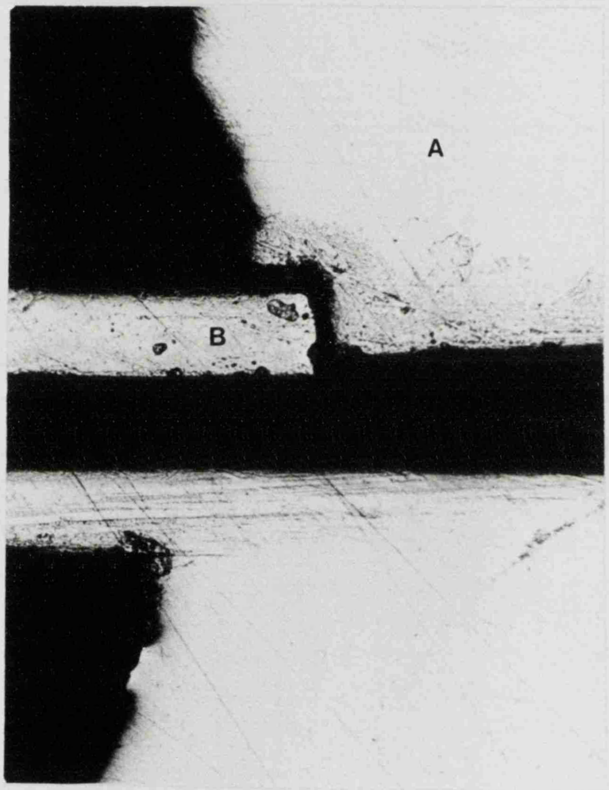


The distribution of failures which occurred during testing of Harper Wyman 18 mm diameter capsules.

■ Top boss weld failure

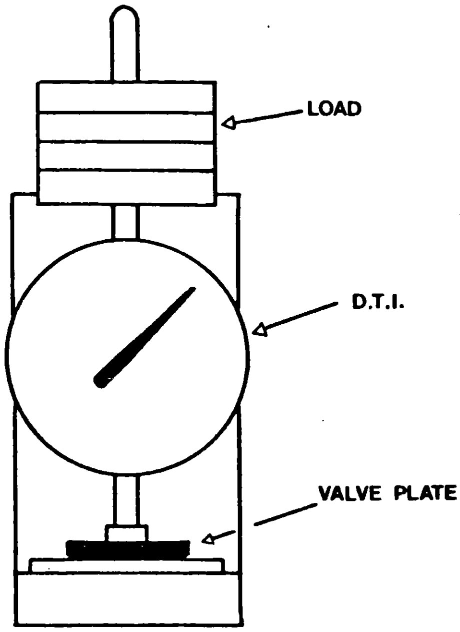
● Other failure

Figure 44



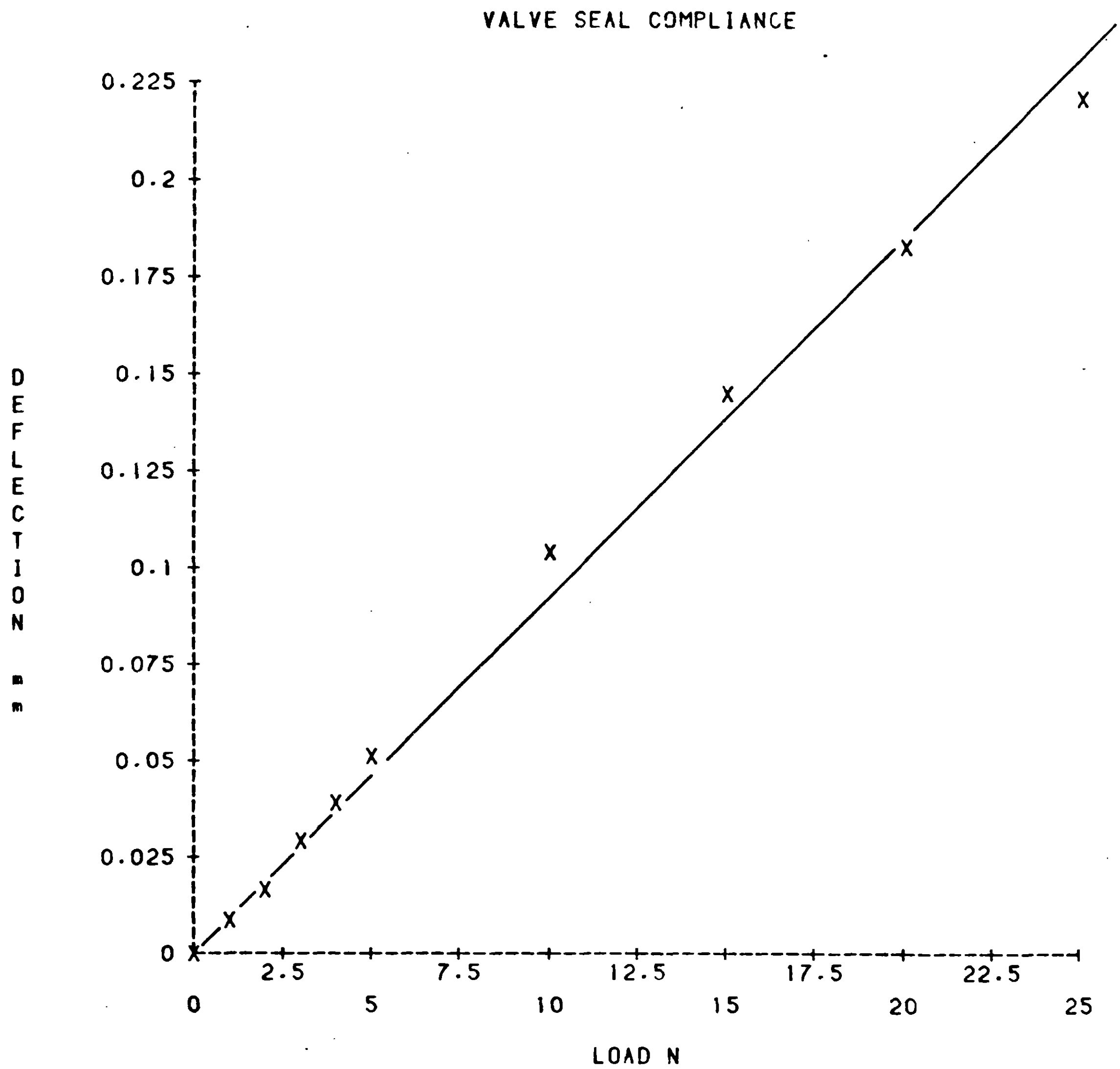
Crack in weld joining top boss (A) to upper diaphragm (B).

Figure 45



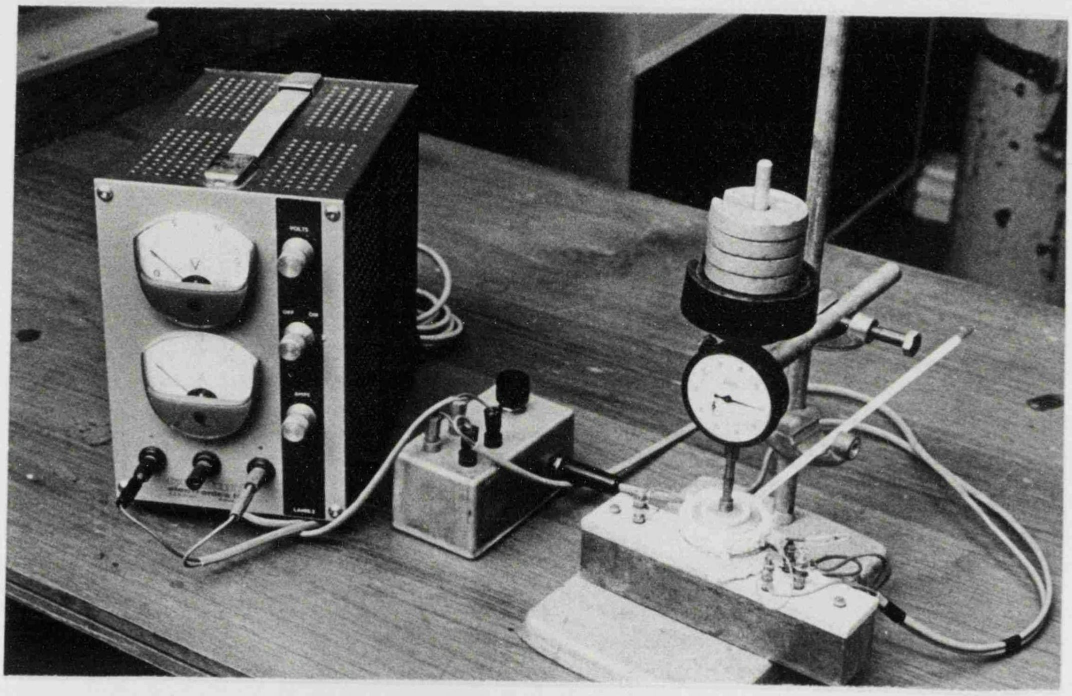
The apparatus for the measurement of the compliance of rubber valve seals.

Figure 46

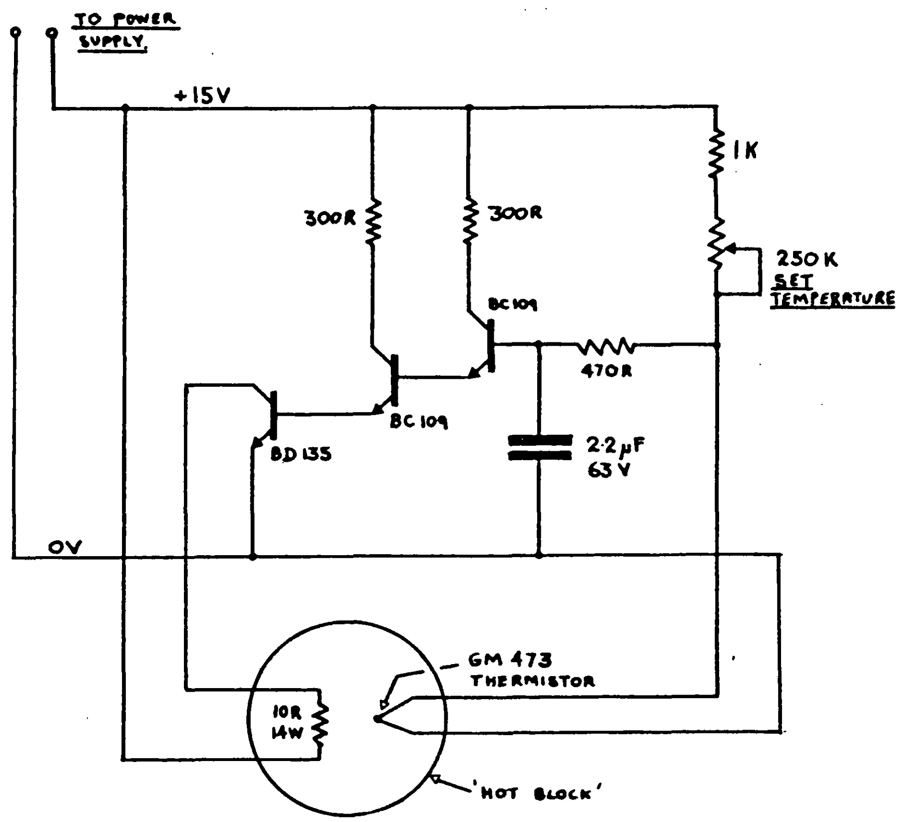


The deflection versus load for a standard Harper Wyman valve plate (see fig. 18).

Figure 47

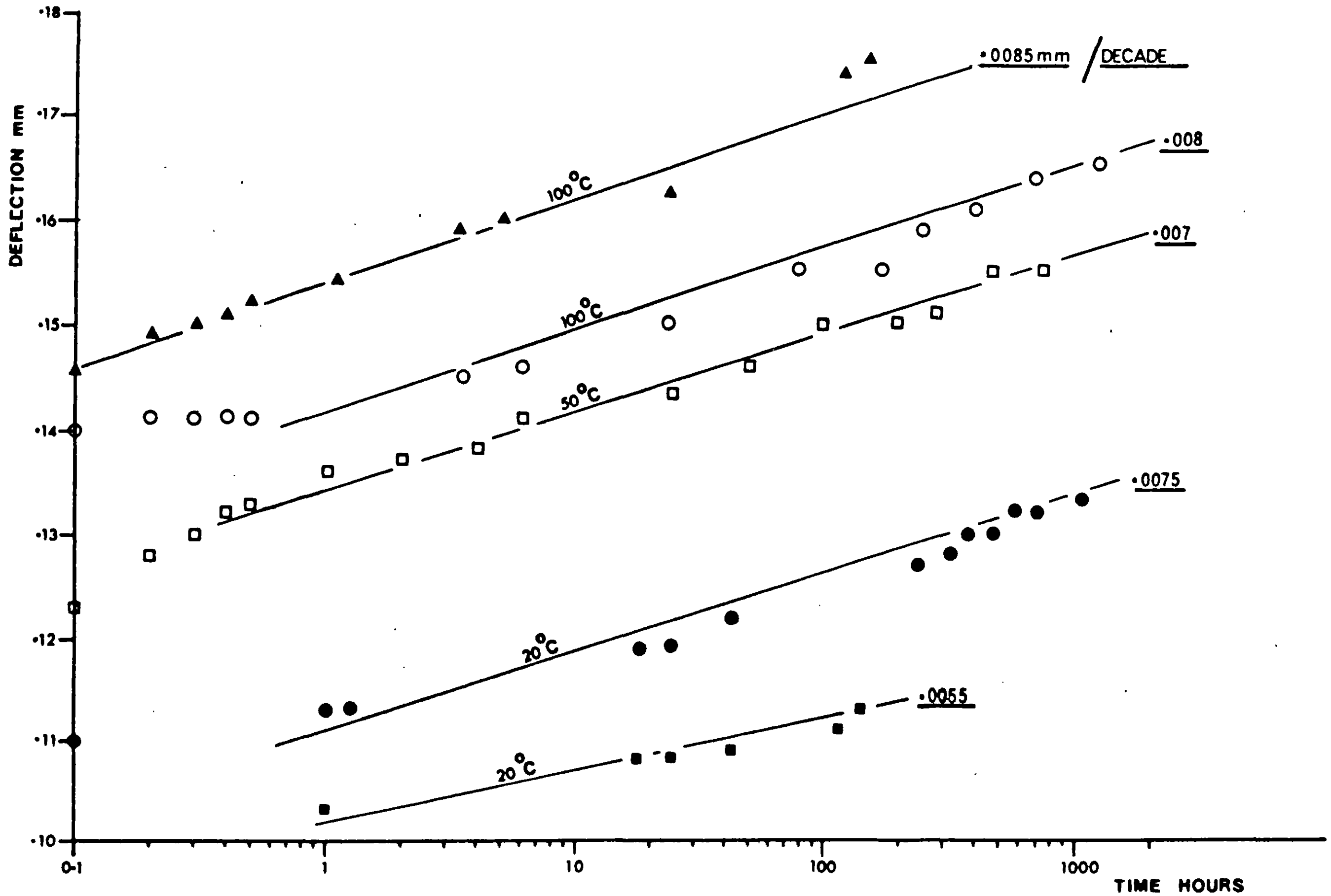


Apparatus for measuring the creep rate of rubber valve seals.



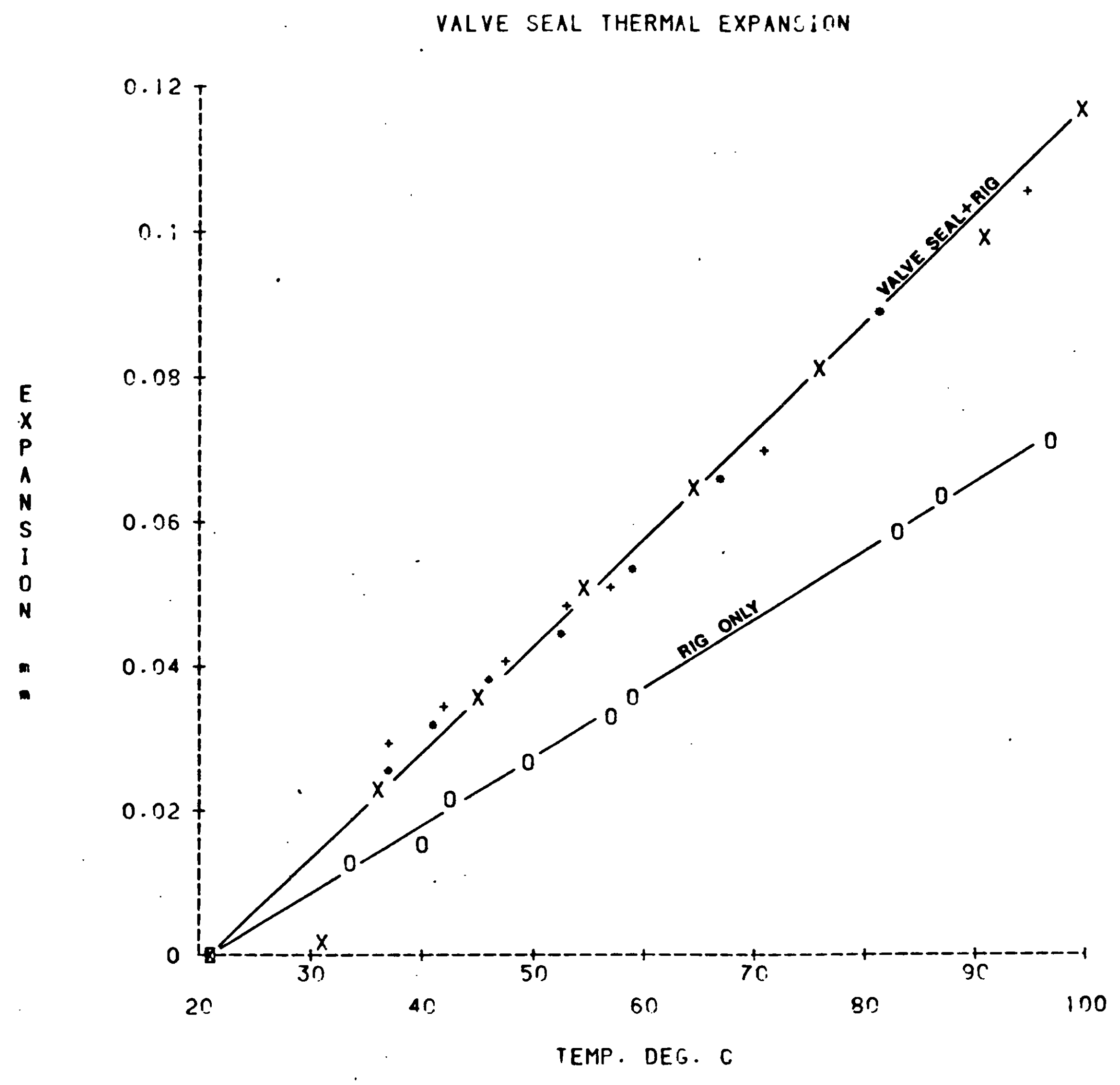
Temperature control circuit for the creep measurement apparatus.

Figure 49



The creep rates of silicone rubber valve seals when subjected to a 10N load at various temperatures.

Figure 50



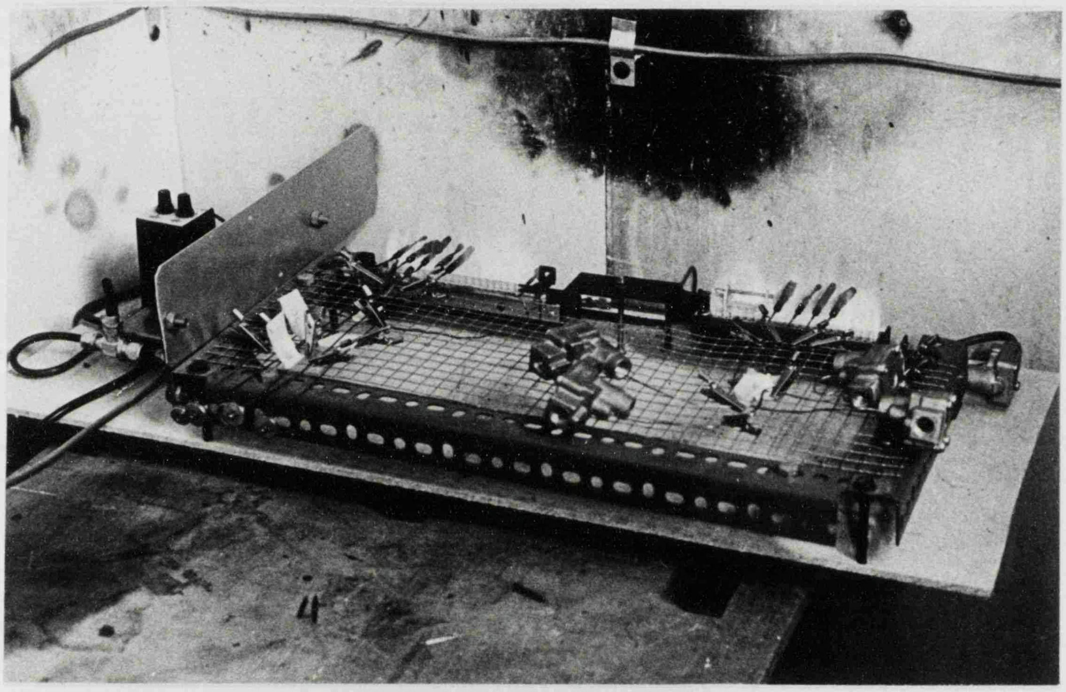
Measurements of the thermal expansion of silicone rubber valve seals.

Sample number 1 = X

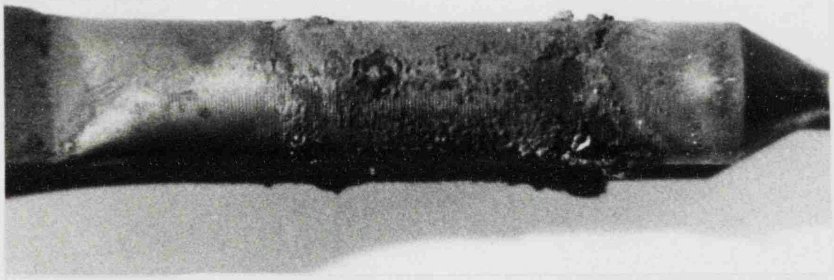
Sample number 2 = *

Sample number 3 = +

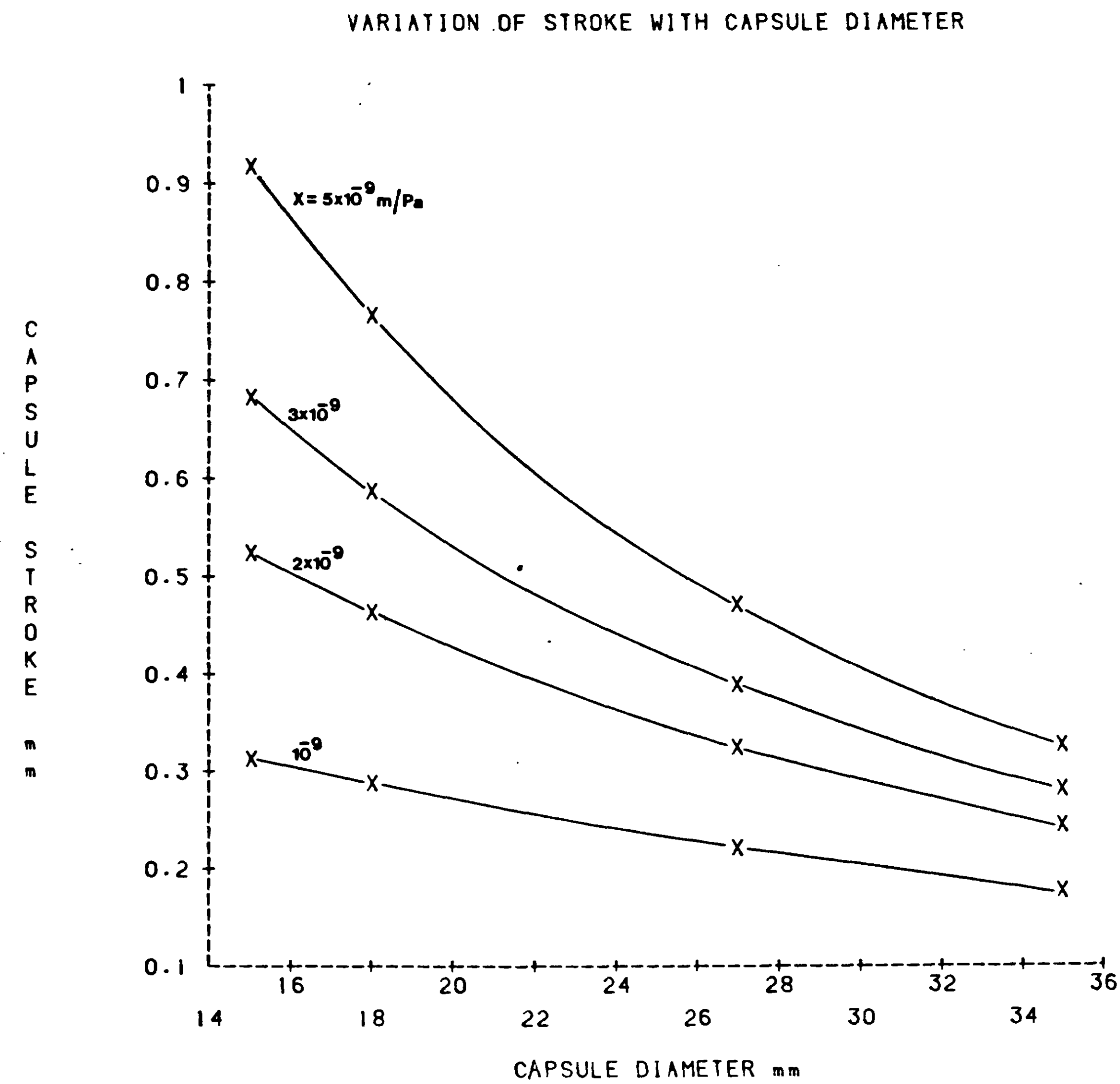
Figure 51



The long term burner test rig.
Thermal systems undergoing continuous flame testing can be seen on the left hand side of the equipment.
Completed valves undergoing cycling flame testing can be seen on the right hand side.



Condition of 500 mm^3 phial after running continuously at 700 ^{o}C in a gas flame for 2,700 hours.

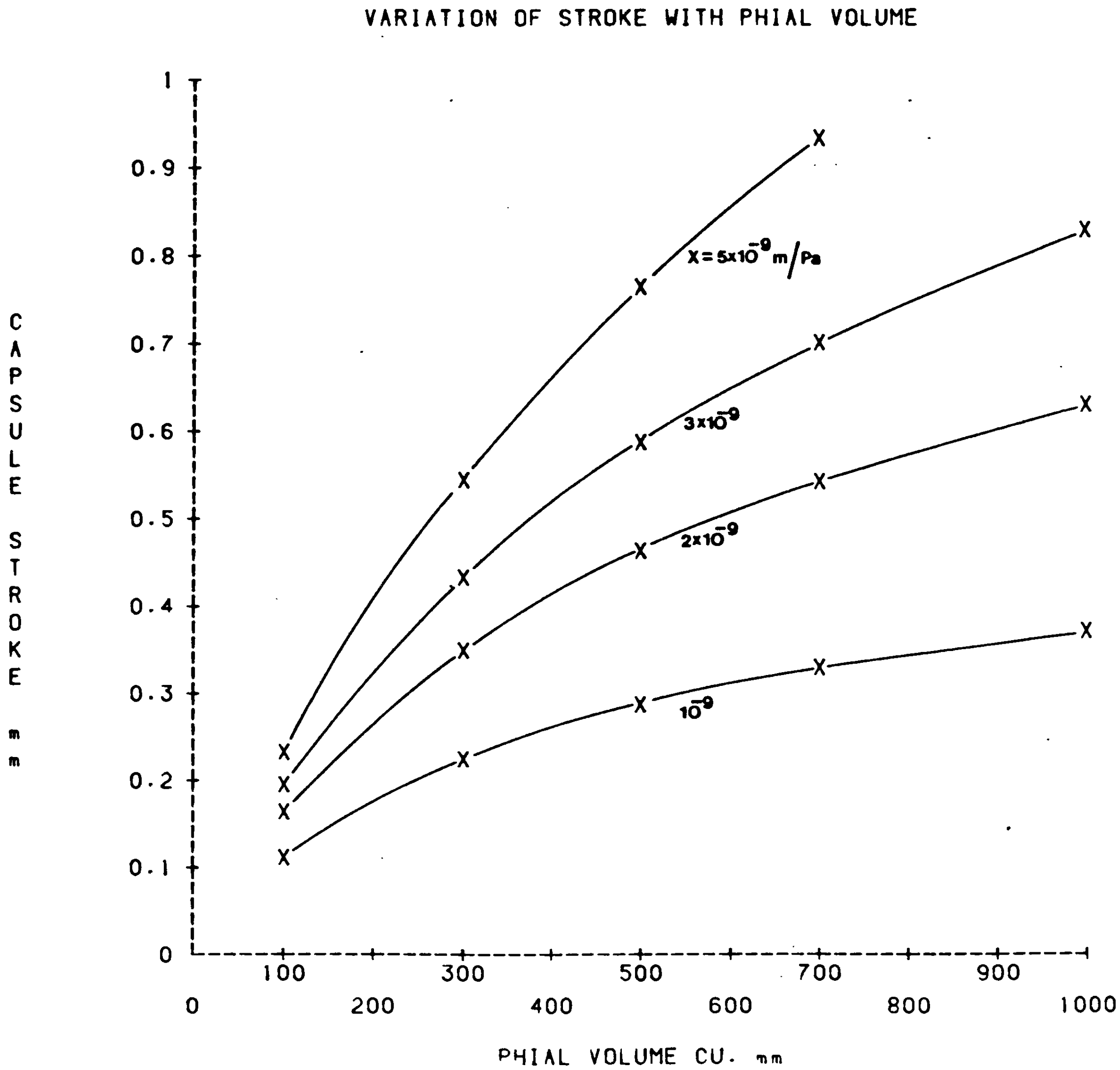


The variation of capsule 27 to 700 °C stroke with capsule diameter.

The other thermal system parameters were:-

V_p = 500 mm^3
P_f = 250 kPa abs.
U = 60 mm^3

Figure 54



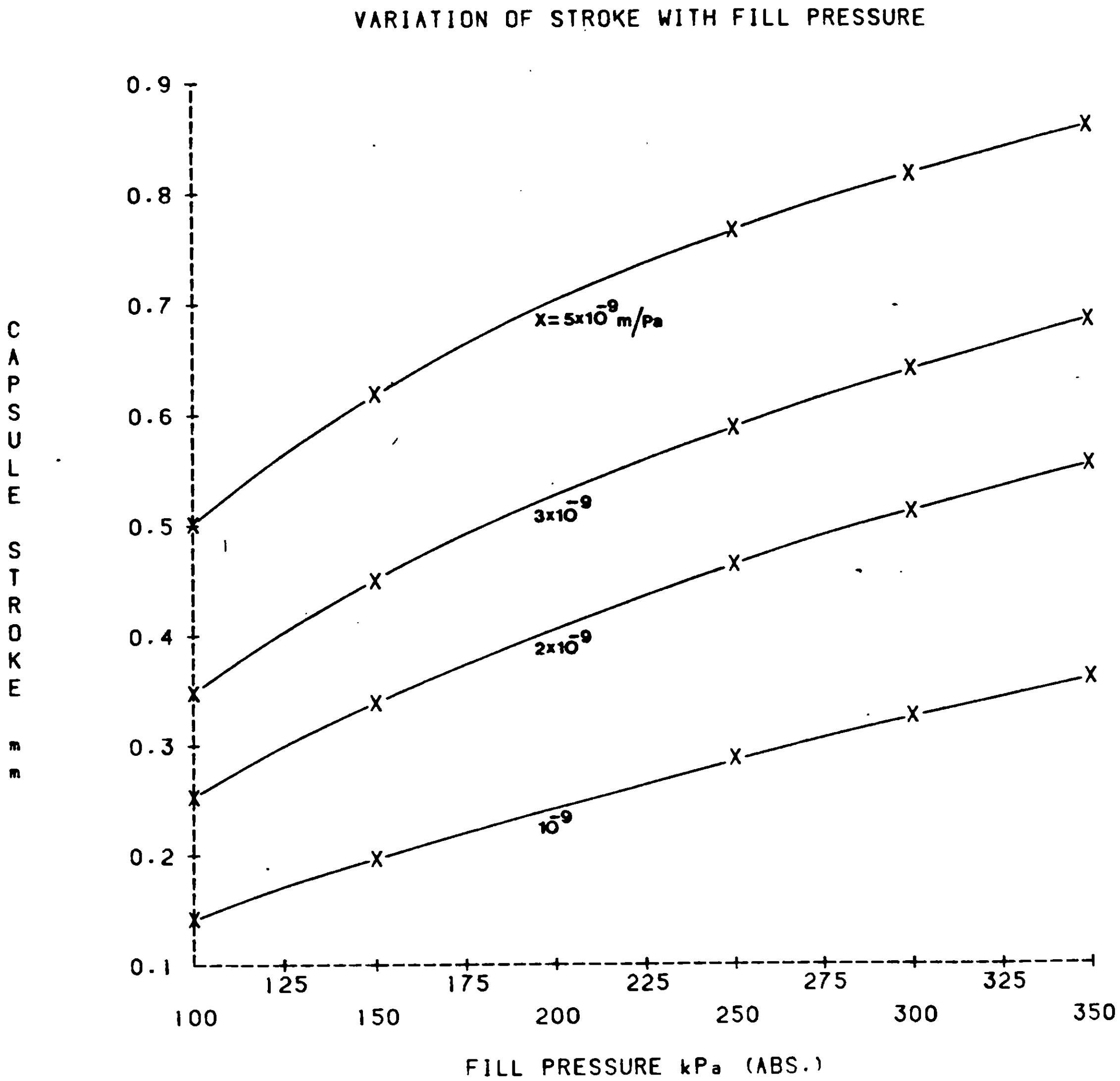
The variation of capsule 27 to 700 °C stroke with phial volume.

The other thermal system parameters were:-

$r = 9$ mm

$P_f = 250$ kPa abs.

$U = 60\ mm^3$



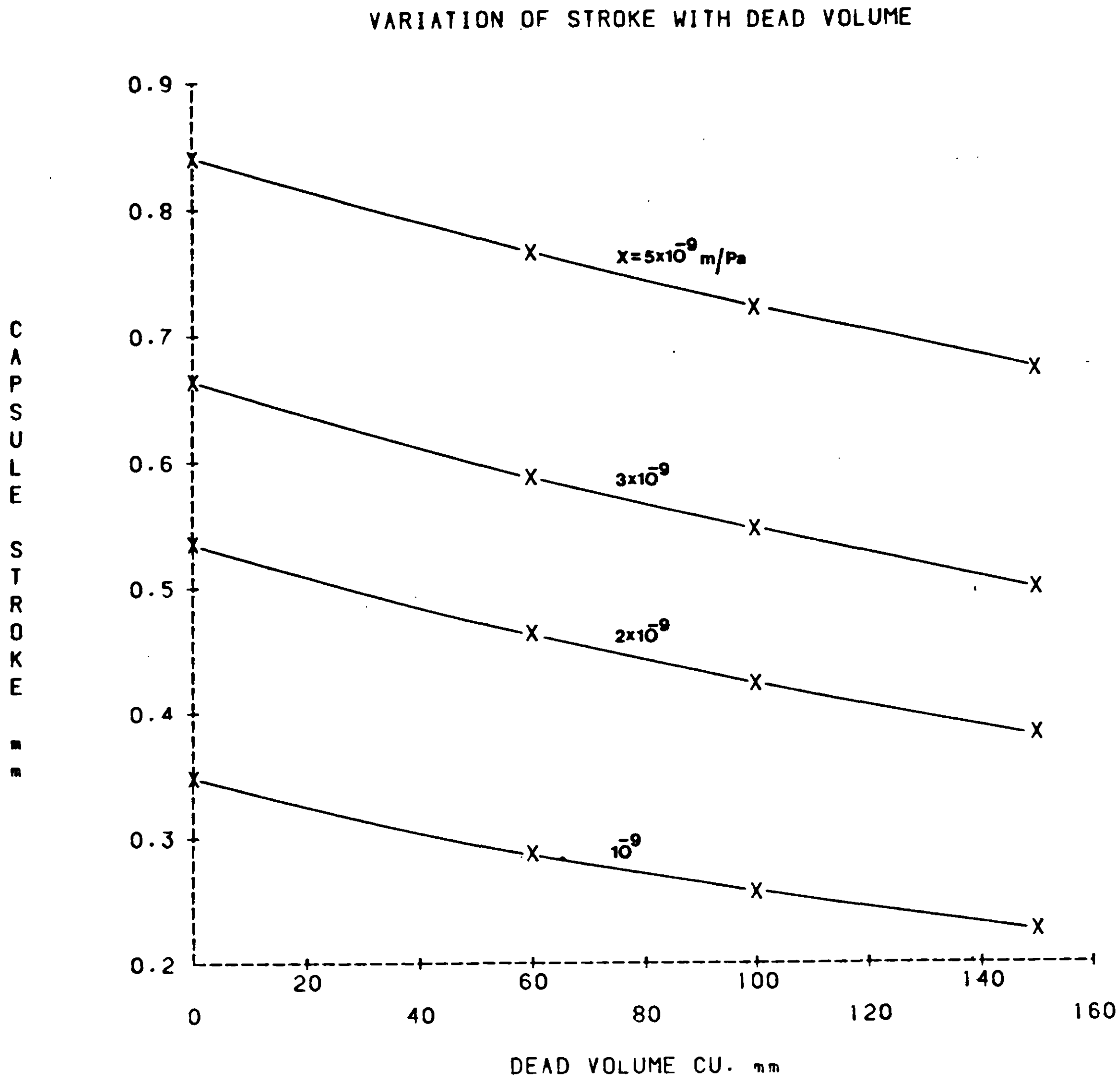
The variation of capsule 27 to 700 ^{o}C stroke with fill pressure.

The other thermal system parameters were:-

$r = 9$ mm

$V_p = 500$ mm^3

$U = 60$ mm^3



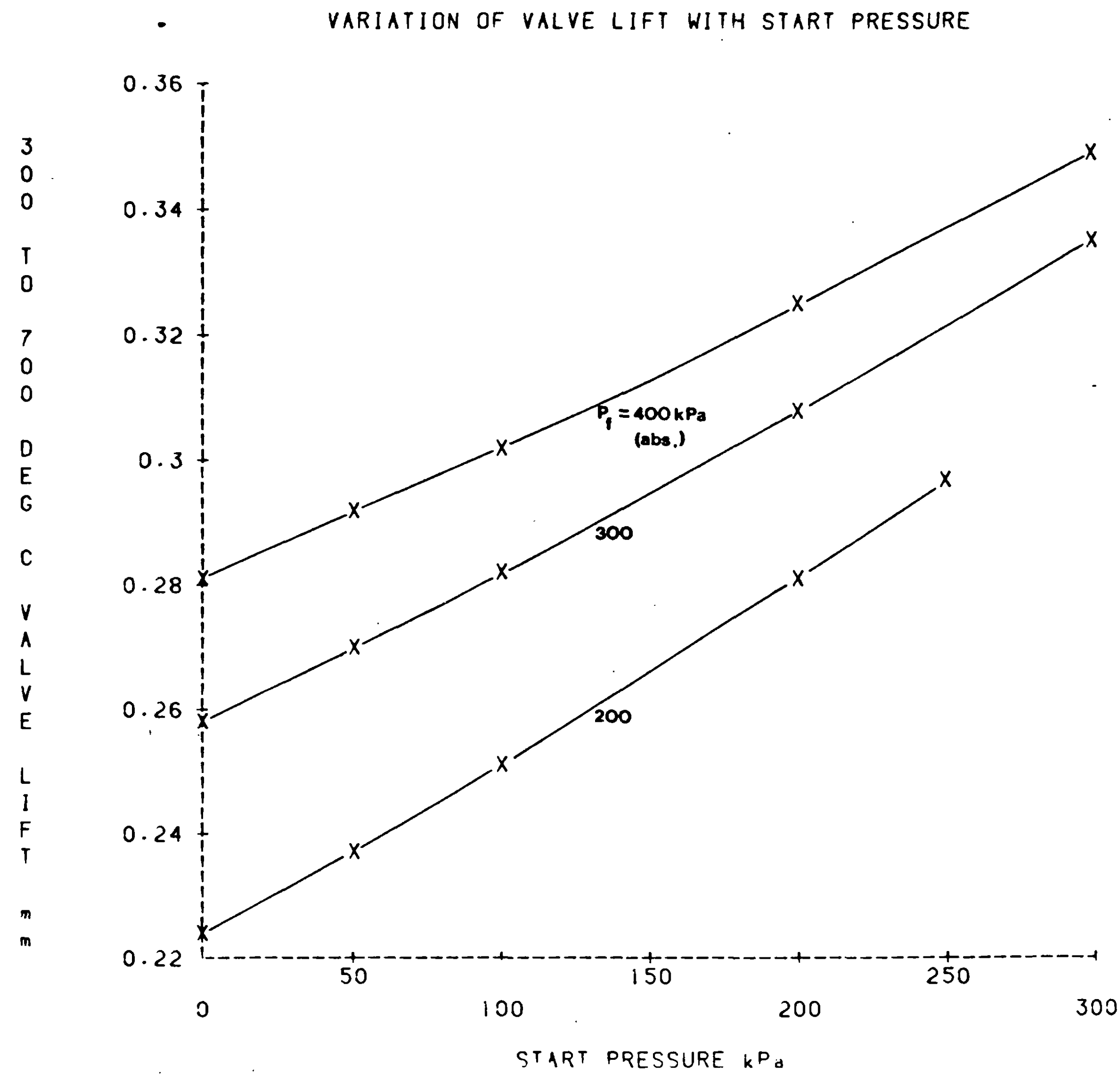
The variation of capsule 27 to 700 °C stroke with dead volume.

The other thermal system parameters were:-

$r = 9mm$

$V_p = 500\ mm^3$

$P_f = 250$ kPa abs.



The variation of 300 to 700 ^{o}C valve lift with starting pressure (P_s).

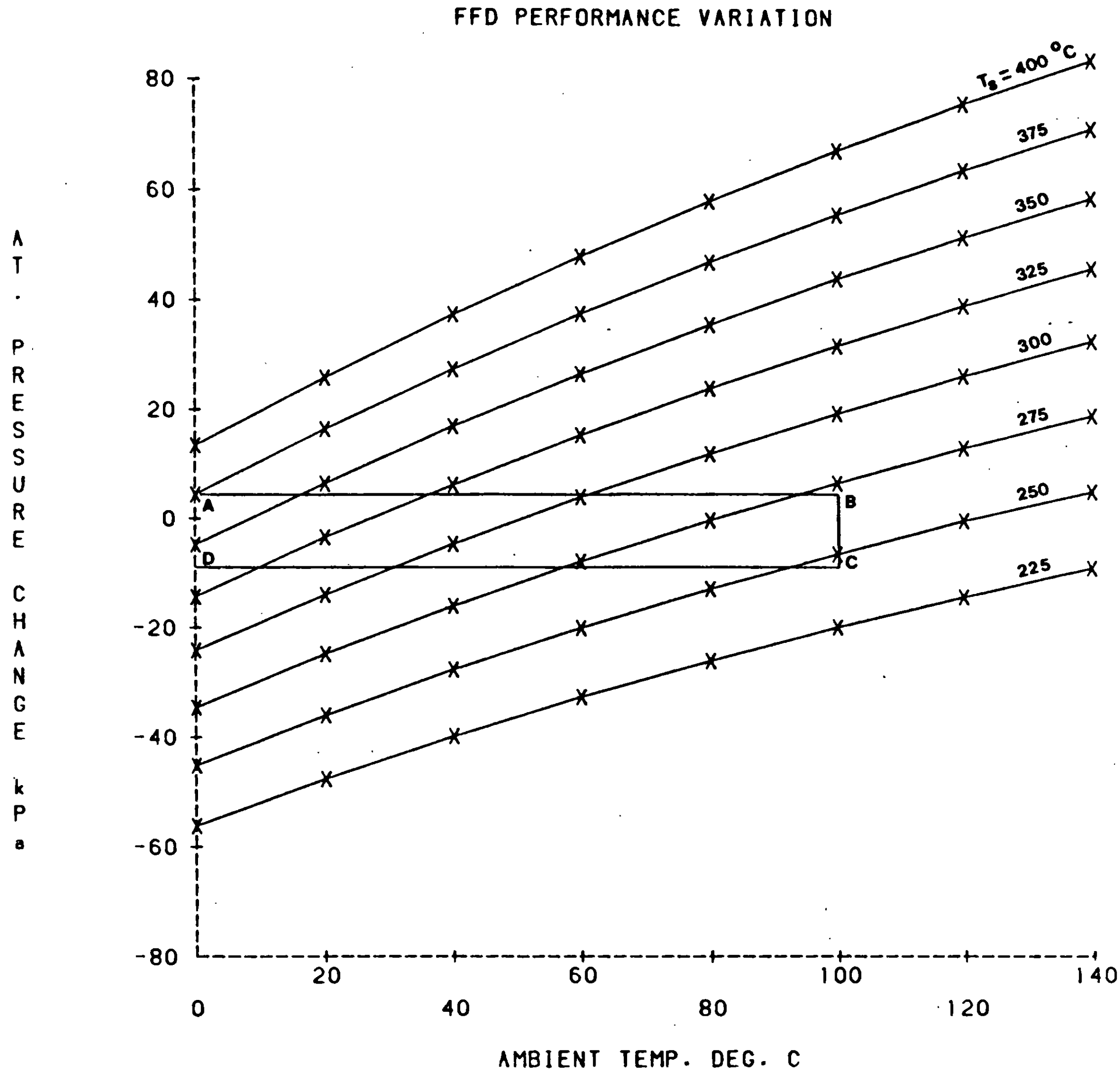
The other thermal system parameters were:-

$r = 9$ mm

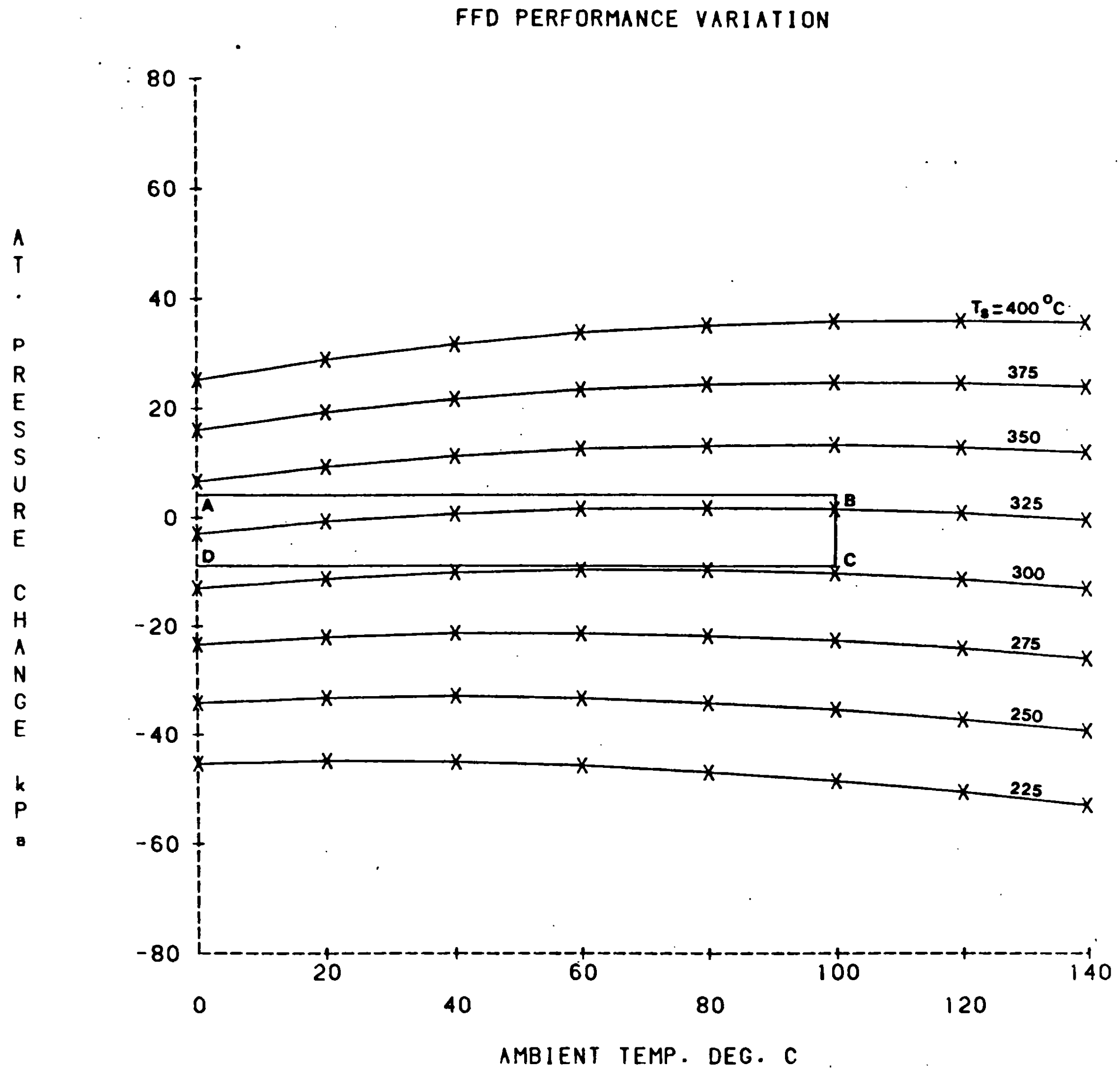
$V_p = 500$ mm^3

$U = 60$ mm^3

$X = 3 \times 10^{-9}$ m/Pa



The variation of opening temperature with atmospheric pressure and ambient temperature for F.F.D. number 31 without any temperature compensation.
The rectangle ABCD indicates the range of operating conditions likely to be encountered in the U.K.



The variation of opening temperature for F.F.D. number 31 with a temperature compensation factor of 0.0007 mm/degree C.

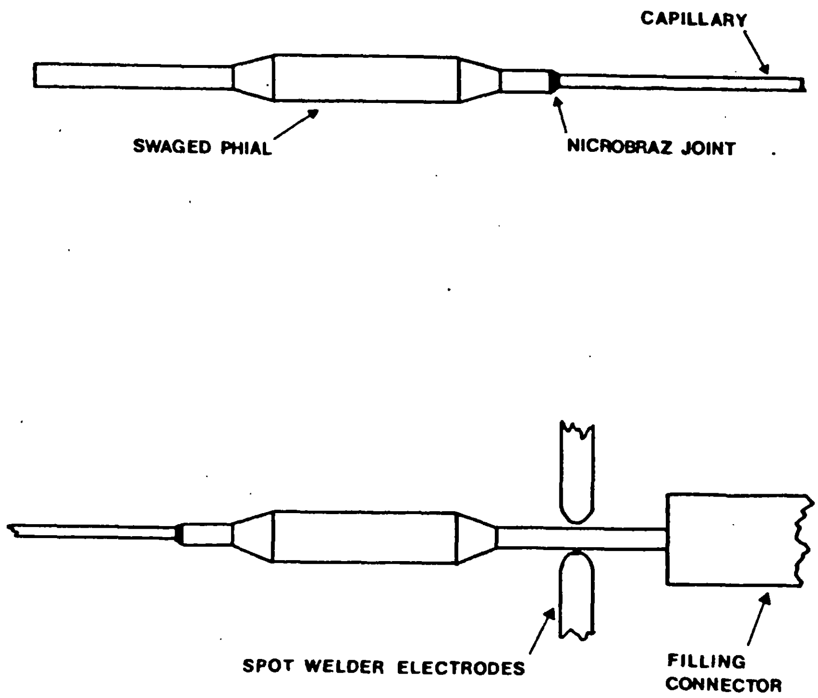
The approximate reduction of atmospheric pressure with altitude is as follows:-

-20 kPa at 1830 m

-30 kPa at 3020 m

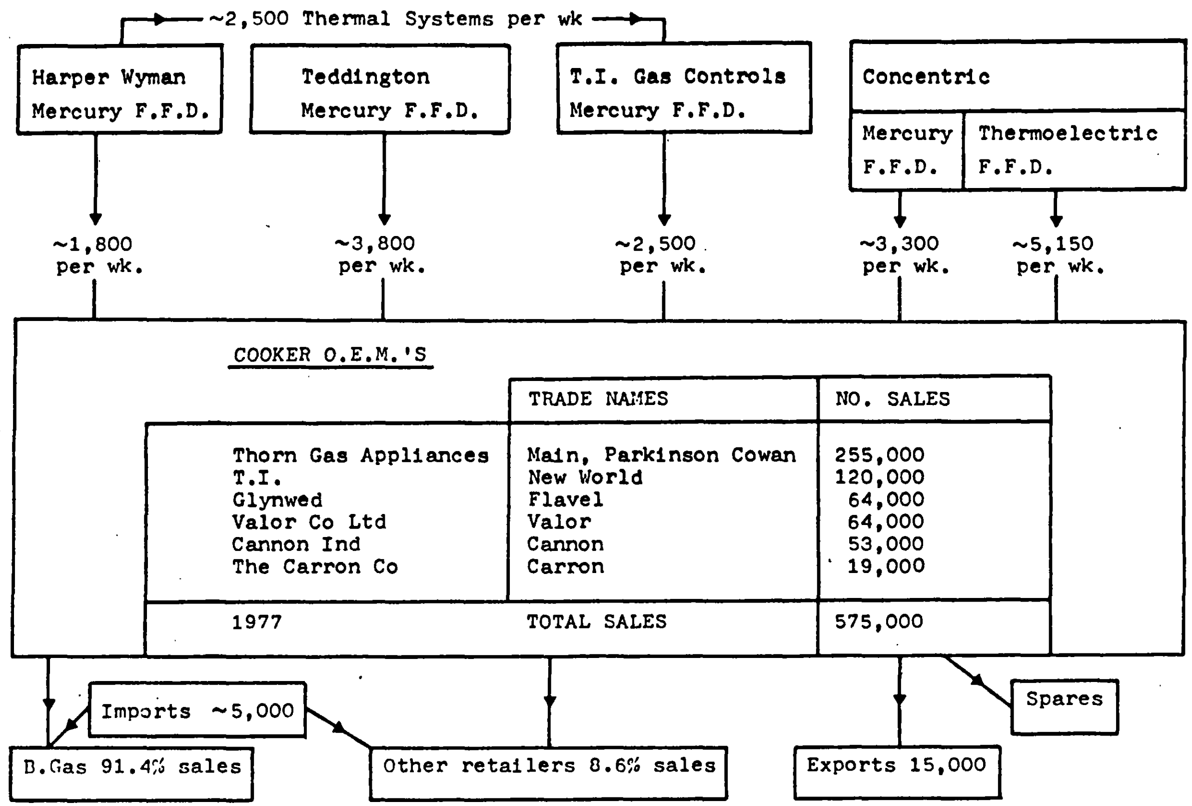
-40 kPa at 4120 m

Figure 60

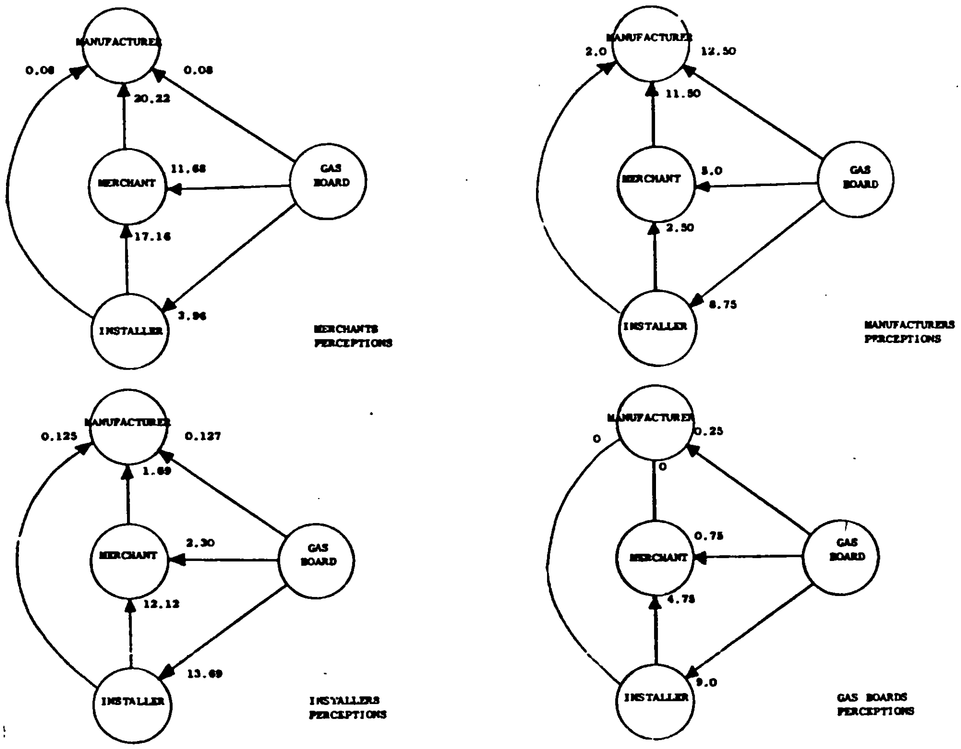


Suggested phial shape and method of filling for a production gas filled F.F.D.

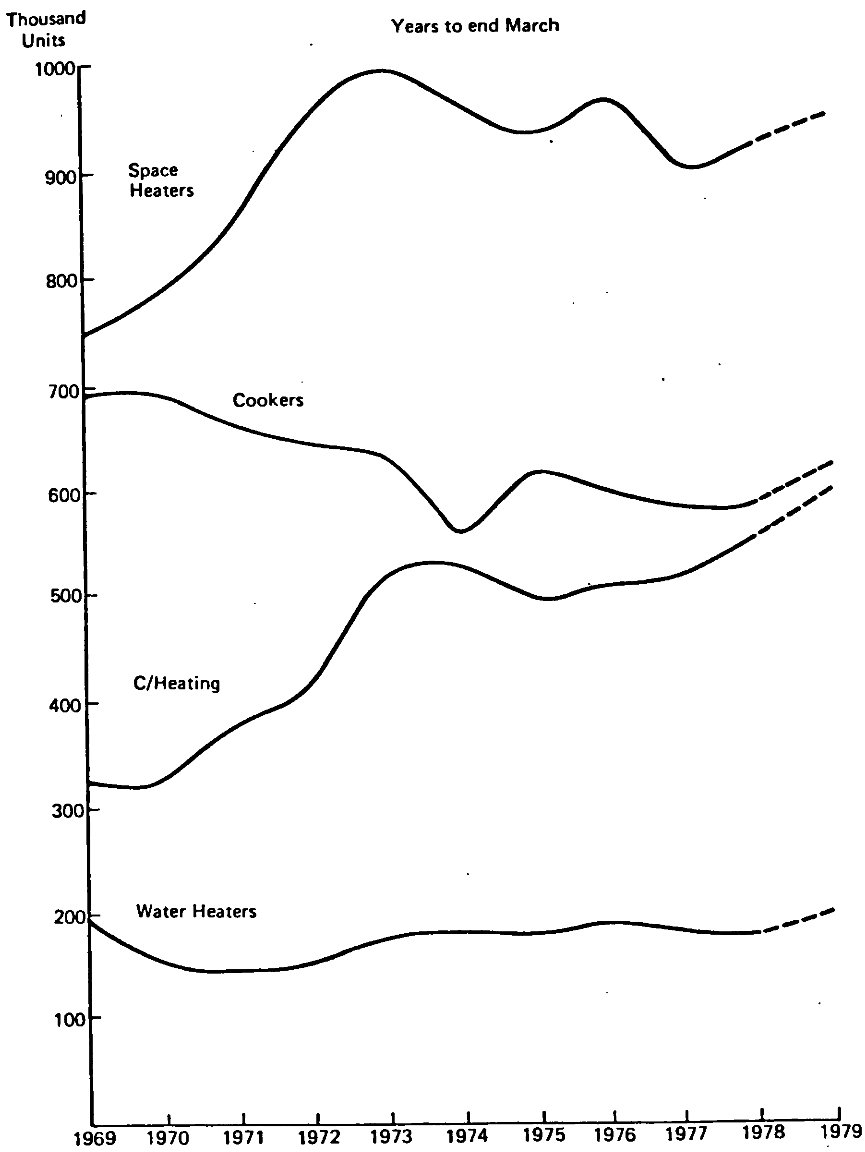
Figure 61



The market channel for domestic cooker F.F.D.s (1977).
Taken from (24) and (69).



Net total-power perceptions for the gas central heating channel.
Taken from Ford (68).



The total annual sales for different gas appliances in the United Kingdom.
Taken from the Monopolies and Mergers Commission report (69).